ELECTRICAL MEASUREMENT.

LOCKWOOD.

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ELECTRICAL MEASUREMENT

AND THE

GALVANOMETER;

ITS CONSTRUCTION AND USES.

By T. D. LOCKWOOD.

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PREFACE.

THE author has made it his aim, in the preparation of this little book, to set forth the principles of electrical measurement and the construction and uses of the most important forms of the galvanometer in as simple and concise a manner as lay in his power, and in language as plain as possible.

All who have passed through the amateur stage of electrical science, know that, irrespective of the clearness and lucidity of explanations made in that science, there remains, owing to the absolute mystery of the force on which it is based—electricity itself—a certain darkness and ambiguity which is very difficult to dispel, and which, to students, is in the highest degree discouraging. Yet, by bringing common sense, common sense language, industry and perseverance to bear upon the subject, much of this darkness may be dissipated.

There is no branch of electrical science more beautiful, more interesting, and we may even say more entertaining, than electrical measurement and testing; yet it is well known that its processes have been contemplated with strong aversion by many to

whom a knowledge of such manipulations would prove invaluable.

Knowledge of the higher mathematics is such an invaluable aid in these processes, that it is not surprising that those familiar with algebra, and the differential and integral calculus, should have availed themselves extensively of such an aid ; it is, however, to be lamented that nearly all the text books on this most important subject assume their readers to be proficient in mathematical knowledge, and use mathematical symbols to explain, or rather to disguise, the most ordinary measurements.

Many students are thus frightened away from galvanometrical tests, for just as the school-boy dreads the processes of arithmetic, and sings the old rhyme :

> " Multiplication is vexation,
> Division twice as bad ;
> The rule of three doth puzzle me,
> And practice drives me mad,"

so the majority of his full-grown brethren regard with suspicion algebraic equations and symbols, whether easy or complicated.

Whatever otherwise may be the faults of this little book, and doubtless they are many, it is the proud boast of both author and publisher that no algebraic equation appears therein, and that arithmetic has been found sufficient for the formulæ contained in

its pages. It is not expected that the information contained herein will be greatly beneficial to experienced electricians; but it is hoped that students, operators, inspectors and amateurs will find it an assistance in their labors and in their pursuit of knowledge, and that it will measurably fill a long-vacant niche in electrical literature.

The best electrical text-books have been, in its preparation, consulted and extensively drawn upon. We are especially indebted to Kempe's "Electrical Testing," Haskins' "Galvanometer, and its Uses," Schwendler's "Testing Instructions," and Thompson's "Electricity and Magnetism."

MALDEN, Mass., March, 1883.

ELECTRICAL MEASUREMENT AND THE GALVANOMETER:

ITS CONSTRUCTION AND USES.

WHEN a man, intending to build a house, a business block, or a factory, goes to buy his land as the preliminary transaction, he has usually calculated the cost, size and character of the buildings he purposes to erect, and he has estimated the quantity of land necessary. Finding a lot which, in other respects, meets his requirements, he ascertains its size by measuring; for if his intention is to put up buildings covering a superficial extent of ten acres, it is hardly probable that he will attempt to do it on a five-acre lot. He will not ordinarily set out to build a block having a frontage of five hundred feet on a land frontage of a hundred feet.

If we are buying our winter's supply of coal, we buy it by the ton, and we want it weighed; we do not care to have the coal dealer guess at the weight, and pay him perhaps for six tons when we receive but five. Similarly, the coal dealer himself finds it to his interest to weigh his coal, as he on his part does not care, as a rule, to receive a cash equivalent for five tons, when he has furnished six.

In carpeting a room, a person with but a grain of common sense, first measures the room, and orders

accordingly, saying: "I want so many yards." He would never think of looking at the room, and then walking off to the carpet store and saying, "Well, unroll your carpet; I'll tell you when there's enough."

In commencing any branch of manufacture requiring power, no one would think for a moment of putting in a hundred horse-power steam engine to do work requiring but one horse-power; neither would we contemplate the desirability of utilizing a donkey engine to set a dozen quartz mills in motion.

The power of the steam engine or other motor is always in some degree at least proportionate to the work to be done.

Thus, in all the daily commercial and mechanical transactions of life, we are accustomed to institute some system of measurement, weight, or comparison, whereby we may intelligently buy, sell, and use the various agencies, necessaries and comforts of civilized life.

Singularly enough, during the early days of telegraphy, and, indeed, until a comparatively recent date, measurements in electricity were scarcely heeded or thought of, and the chapter of accidents was, in a great measure, trusted to, in the construction and maintenance of a line of telegraphy.

The line was built, perhaps, of several gauges and grades of wire, the ground plates consisting of two

or three turns round a rusty gas-pipe at both termini, the battery entirely disproportionate to the work—perhaps much too large, perhaps much too small, the relays varying from one hundred, to four hundred ohms, the insulation defective and irregular, and the local circuits likely enough having two-ohm sounder magnets and six-ohm batteries.

In fact, while carrying the exact sciences into every common transaction of the day, we departed from common sense and exact measurements where both elements were, if anywhere, most requisite with the results that might be expected, *i. e.*, irregular, poor-working lines, yet withal much higher in first cost and maintenance than if they had been properly constructed on a basis of electrical measurements, thus insuring a proper proportion between the different elements of the line.

There is no force of nature, however, that is more subject to her unchangeable laws than electricity, and many of those laws, and the measurements and testing methods depending thereon, are so exceedingly simple, that a child may readily master them.

Every telegraph operator, every telephone manager or inspector, and every person engaged in any employment in which electricity is used, should be conversant with simple testing and measurements.

Not only is such knowledge a most useful acquirement, but its practice is interesting and

fascinating in the extreme, even if indulged in merely as a pastime. Just as in the cases and circumstances instanced, we employ weights and measures; so we may in the applications of electricity, employ various measurements for many purposes, and we shall find that by basing our practice on these measurements, we shall have both better and cheaper results.

As also we commonly employ suitable instruments and apparatus in weighing and measuring tangible substances, using scales or balances for those bought and sold by weight, tape measures and rules for measurements, and clocks and watches to mark the advance of time, so we find it essential in the valuations and comparisons of electricity to use suitable instruments.

These instruments are called galvanometers, and are capable of being used to measure, compare and estimate many of the different properties and magnitudes of electricity. By their aid we may readily ascertain and compare the working strength and value of electric currents, the resistance which electro-magnets, wires and other conductors offer to the passage of the current, the electro-motive force or initial power, and the resistance of batteries; and we are also enabled by their use to localize line troubles and other circuit faults.

As batteries are essential in all electrical measurements, they will be now briefly referred to.

BATTERIES.

The most suitable battery for use in connection with galvanometers, at least in ordinary measurements, is the blue vitriol battery in almost any of its well-known forms.

That type known as the Crow Foot Battery is to be commended as a thoroughly efficient form, and is now in general use on telegraph lines, both for "main" and "local" purposes.

This battery is shown in Figure 1, and, as plainly indicated, is of the most simple nature; consisting practically of but three parts, *i. e.*, the zinc, copper, and containing vessel.

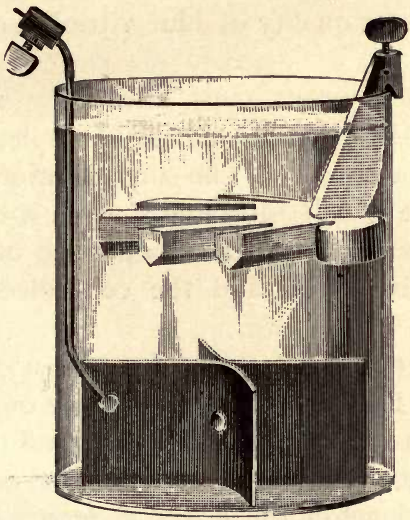

Figure 1.—THE CROW FOOT BATTERY.

The Leclanche battery also gives very fair satisfaction, and inasmuch as it is now universally employed for many purposes, and is well known to almost every one, it is here noted as being adapted for this purpose, and recommends itself as being always at hand or easily procurable.

Both forms of battery are so familiar to every one engaged in electrical pursuits, that no description of either is here necessary. A few words on the management of batteries may not, however, be out of place.

If the Daniell, or gravity battery be chosen, and these are preferable on account of their greater constancy, the best quality of blue vitriol ought always to be used.

Never use porous cups after they are at all cracked, or in any way damaged, or let the zinc touch the porous cup. The zinc solution is at its best when it is half saturated; when it is stronger than that point of saturation, a portion of the fluid should be drawn off and the cell filled up with water.

When a gravity battery is first set up, the poles ought to be united by a wire for a day or two; this will tend to separate the solutions and to concentrate the zinc solution.

Keep the level of the water at least a quarter of an inch above the zinc. The copper plate ought

always to be immersed in the blue solution, and the zinc in the sulphate of zinc solution.

The line between the two solutions should be kept as sharp as possible. If the blue is too low, a little of the zinc solution should be withdrawn and replaced with pure water, and the battery circuit left open for a while.

If the blue is too high, the battery ought to be short circuited by uniting its poles with a wire for a while.

If a froth generates on the surface, it may be removed with a piece of wood or a brush.

When the zincs become dirty, they should be taken out, scraped and washed.

When the Leclanche battery is employed, the following directions may profitably be complied with: Never let the sal-ammoniac solution rise above the shoulder of the jar. If a new battery is set up and wanted at once, a little water should be poured into the porous cup. The sal-ammoniac solution should be strong, but too much sal-ammoniac should not be put into the jar at once, as it is likely to cake, instead of dissolving.

If, on the contrary, there is not enough in the jar, crystals will commence to form on the zinc, and the power of the battery will be impaired.

The connecting wires of a Leclanche battery should be occasionally looked over, as the free

ammonia generated by the cell is likely to eat them through.

If a battery consisting of a number of cells is weak, and no cause is apparent, each cell should be tested separately, and when the defective cell is found and examined, the lead cap surmounting the carbon will probably be found to be insulated from the carbon by a salt of lead formed under it.

If, by any accident, the Leclanche battery cell be left on closed circuit, and run down, its strength may be to a certain extent renewed by soaking the porous cups in water, or dilute muriatic acid, and giving the battery a considerable rest.

In all batteries, to produce good work, every point of contact and every connection should be kept clean and bright, and every screw well tightened up.

It is found convenient to illustrate a battery cell by the symbol or conventional sign of a thick and thin line of different lengths, as in Fig. 2, a number of cells being similarly represented by a series of these, as shown in the same figure.

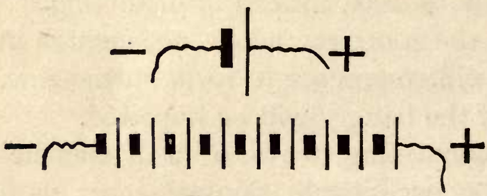

Figure 2.

The short, thick lines are usually intended for the zinc, and the longer, thin lines for the other plates.

The plus sign, +, at the end of the battery designated by the thin line denotes the positive, and the minus sign, —, at the other end the negative pole.

DEFINITIONS OF ELECTRICAL TERMS AND UNITS.

In order that we may clearly understand the galvanometer, and when, why, and how to use it, it is proper that we should have, at the outset, a full comprehension of the meaning of the technical terms commonly used to express the different properties, magnitudes, functions and relations of electricity and electrical conductors, and of the units which indicate the value of such properties.

ELECTRO-MOTIVE FORCE.

Electro-motive force is the name given to the initial power of any source of electricity. If the force originates in a battery, it is produced by the difference in chemical action on two metals in a liquid.

It expresses for electricity what the pressure in a boiler does for steam, and would express the strength of the current if a circuit could be made having no resistance.

But, as in the case of steam, much of the power is lost by friction in the pipes and by radiation

between the boiler and the cylinder of the engine, so in electricity, the useful effect of the electro-motive force is greatly diminished by having to overcome the resistance both of the source itself and of the conductors it traverses. The electro-motive force of any battery, then, may be defined as "the power which it has to transmit a current against resistance," or its power to overcome resistance.

It increases in direct proportion to the number of cells employed, ten cells having exactly ten times the electro-motive force of one cell.

It is not, however, dependent on their size; a cell no larger than the bowl of a tobacco pipe possesses as great an electro-motive force as a cell with the same kind of plates and liquids which would hold a gallon. If we have to work a long circuit, or one of high resistance, we require a strong initial force, and we get it by increasing the number of cells. It is convenient to use the abbreviation E M F to express the term electro-motive force.

POTENTIAL.

Electrical potential is to electricity just what temperature is to heat, and level or height to water. The word "potential," literally, means the power of doing work; electrical potential implies something more; it indicates the electrical condition of any body, and not only that electricity has power to

do work, but also that it is in a condition to exercise that power.

The word "tension" is frequently used by the older writers upon electricity, and has substantially the same meaning as "potential," *i. e.*, a condition of readiness to do work, such as that of a bow, during the moment when the string is drawn as tense as it can be, just before the release of the arrow.

Comparing electricity with heat, it is perfectly clear that to transfer heat from one point to another, it is first necessary that the two points shall be of different temperature. Just so with electricity. To nroduce a current, it is requisite that the two poipts which are united by any conductor shall be of different potentials, and when such is the case, electricity flows from the higher to the lower potential.

POTENTIAL, OR TENSION, AT ANY POINT.

The electrical potential of the earth is assumed to be zero. When we speak of the electrical potential of any point in a voltaic circuit, for example, an ordinary telegraph line, we mean the difference in electrical condition between that point and the zero point.

To illustrate the idea, let us imagine that we desire to connect telegraphically two points, ten miles apart, and that our electrical power consists of ten

cells of battery connected up in the usual way; that is, in series, or one after another.

If we construct a single line and make a ground circuit, connecting one end of the line with the earth, the other end of the line with the positive pole of the battery, and the negative pole of the battery with the ground, we now have a complete circuit. The negative pole being united to the earth, has the same potential as the earth; *i. e.*, zero.

The distant end of the line being also united to the earth, has also a zero potential. Let us further suppose the EMF of every cell to have the value of ten units; this gives for the ten cells a total EMF, or difference of potential between the two extreme poles of the battery, of ten times ten, or 100, which then must be the potential of the circuit at the positive pole, where the line is united to it; and because the positive pole is to line, the potential is 100 +, or above zero.

The potential now, at any point in the circuit, is ascertained by dividing the total resistance into 100 imaginary equal parts, through which the potential gradually falls, till it reaches zero at the distant end.

Thus, in the case assumed, where the potential at the junction between the battery and the line is 100, that point in the line where its resistance is exactly halved will have a potential of 50; and if we divide the total resistance into quarters, the

point denoting the quarter line nearest the battery would have a potential of 75; and that nearest the distant end of the line a potential of 25, as shown in the diagram Figure 3, in which the sloped line

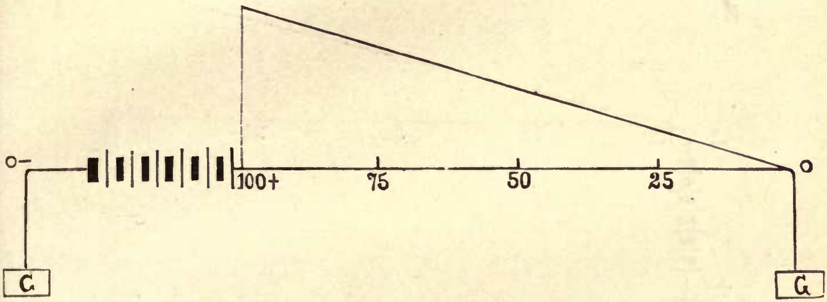

Figure 3.

denotes the gradual fall of potential from the battery end, where it is highest, to the distant ground end, where it is lowest.

If, on the contrary, we reverse the battery, uniting the negative pole to the line and the positive to the earth, the positive pole would acquire the zero potential of the earth, and the negative pole a potential of 100 below that of the earth; and in this case the potential rises as the distant end is approached, and will, at the junction of the battery with the line, be 100 —, or below the potential of the earth; at the first quarter of the distance 75 below, at the middle of the line 50 below, and at the last

quarter 25 below the zero of the earth, as shown in Figure 4.

In this case, the line of slope represents the gradual rise of potential.

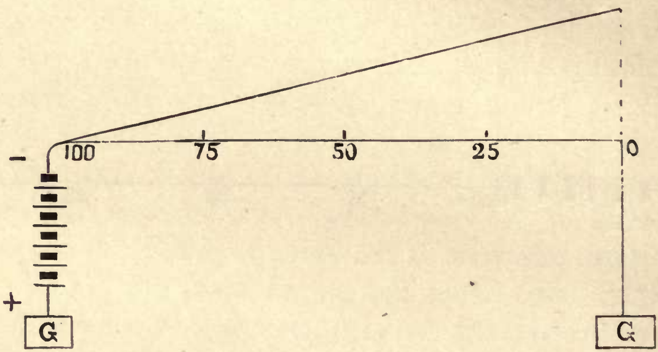

Figure 4.

If we have a battery at both ends of the line, of course the battery at one end will have the positive pole to line, and that at the other will have the negative pole to line.

In that case, still assuming that each battery has ten cells, each cell giving an E M F, or difference of potential of ten, the entire difference of potential between the battery at one terminal station and that at the other will be 200, as illustrated in Fig. 5; for as we see the potential at the ground plate of Station A is zero, being in contact with the earth, from that point to the positive pole *a* it rises to 100 +, going

out to line, the potential falls regularly to a point where the resistance of the circuit is exactly halved, and at that point it again reaches zero.

Continuing to fall, at the point *b*, where the negative pole of the battery is united with the line, it is 100 —. Here it commences again to rise, and at the ground end of this battery it is again zero.

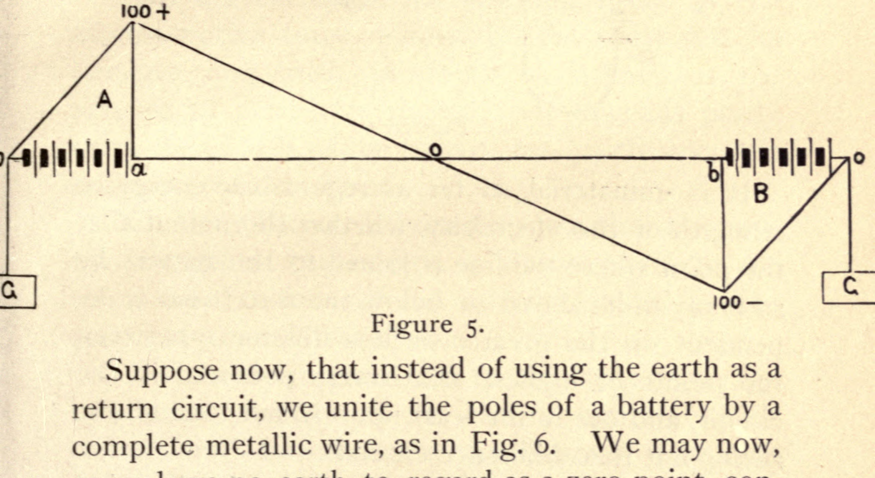

Figure 5.

Suppose now, that instead of using the earth as a return circuit, we unite the poles of a battery by a complete metallic wire, as in Fig. 6. We may now, as we have no earth to regard as a zero point, consider the center of our battery to be the zero; then the positive pole will be + and the negative —, and if, as before, we assume the difference of potential between the poles to be 100, the potential at the positive will be 50 +, and that at the negative pole 50 —, and the potential will fall regularly along the line from the positive pole, and rise regularly from

the negative pole, until they both meet in the middle of the wire, where the potential will be zero.

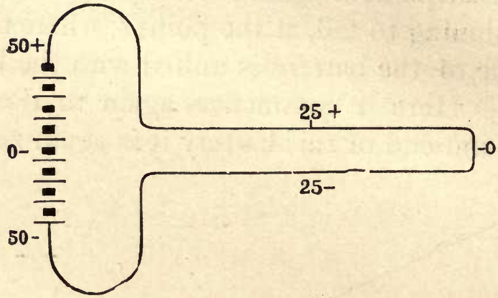

Figure 6.

It is immaterial, so far as regards the energy or strength of the electricity, whether the potential at the point where the line is joined to the battery be so many units above or below the zero; that is dependent on the greater or less difference between the points of highest and lowest potential in the circuit, and not in the least upon which side of the zero point that difference extends.

This condition, however, determines the direction of the current, because electricity always moves from a higher to a lower potential.

We have thus, at some length, endeavoured to make these ideas clear, because the Wheatstone Bridge system of measurement—the most beautiful and convenient system ever devised—depends entirely upon the principles here enunciated.

CURRENT STRENGTH.

We use the word "current" to denote a continuous flow of electricity. The strength of current is the working power of the electricity after it has overcome the constant resistance of the circuit, or the amount of electricity actually traversing the circuit.

Since the current is the working result of the electro-motive force divided by the resistance, its strength may with propriety be defined as the amount of electricity realized. It depends partly upon the E M F of the battery, and partly upon the resistance of the circuit.

When any battery is joined up in a closed circuit, the strength of the current is always equal to the electro-motive force of the battery, divided by the total resistance of the circuit.

This is the simplest and, at the same time, the most important law of the electric current. It is called Ohm's Law, because the German mathematician, Professor G. S. Ohm, first announced it.

We may illustrate the difference between the E M F of the battery, and the strength of current flowing in the circuit, in the following manner: A battery has an E M F of 100, we join it up in a circuit having a total resistance of 50 ohms; the strength of current, therefore, is 100 divided by 50, which is 2.

We shall presently find occasion to re-state Ohm's Law in somewhat different and more definite terms.

RESISTANCE

Is the name given to the obstruction or opposition to the passage of electricity offered by the substance of the circuit through which it passes.

Every substance offers some resistance, and, in fact, it is the different degrees of resistance offered by substances that determines their division into conductors and insulators. Conductors have low, and insulators very high resistance. Some metals also have a much higher resistance than others.

A conductor having a high resistance does not let the electricity pass so freely as it would in a conductor of low resistance; that is, the quantity passing in a given time is diminished.

The resistance of a battery circuit is made up of the resistance of its several parts, *i. e.*, the wires, the instruments, and the battery.

The two former we call the external, and the latter the internal resistance.

The internal resistance of a battery consists in the resistance of the liquids and of the porous cell, if one is used. It increases in direct proportion to the number of cells used; that is, if one cell has an internal resistance of one unit, a battery of ten similar cells will have a resistance of ten units.

The resistance of any wire increases in proportion to its length. If the resistance of a mile of wire be ten units, that of fifty miles will be fifty times ten, or five hundred units.

The resistance of any wire is inversely proportional to the area of its cross section, that is, the resistance of a wire increases as its weight decreases.

JOINT RESISTANCE.

If a circuit divides, as in Fig. 7 at A, into two branches which meet again at B, the current of electricity passing through the circuit will also divide,

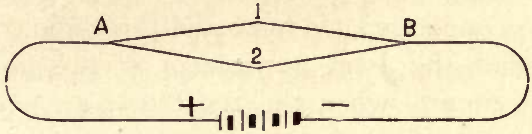

Figure 7.

part flowing through one branch, part through the other. The strength of current in the two branches will be inversely proportional to their several resistances.

Thus, if a current with a value of 50 be flowing in the main circuit before dividing, and if the branch circuits 1 and 2 be equal, half of the current will flow through the wire 1, and half through the wire 2, the current in each branch having a value of 25.

Or, if the resistance of branch 1 is three times that of 2, one-fourth of the current will pass through branch 1 and three-fourths through branch 2. The *joint resistance* of the divided circuit will be less than the resistance of either branch considered alone, because the conditions are exactly the same as if the one wire was taken off and a larger one substituted therefor, with a conductivity equal to the two wires. Therefore, we see that the term "joint resistance" means literally the resistances of two or more wires treated as one.

If we add a third wire, making three branch circuits, and the resistances of all are equal, the joint resistance is now but one third of the original wire, and the conductivity is increased three-fold.

To find the joint resistance of two or more parallel circuits when the resistances are equal, we may choose either of several methods. One way is to divide the resistance of one wire by the number of wires. For example: 5 wires each have a resistance of 60 ohms; to obtain the joint resistance of the 5 wires, we divide the 60 by 5, and the quotient being 12, 12 is the joint resistance required.

Or we may, if there are only two wires, divide the product of the respective resistances by their sum. To illustrate: Two wires each have the same resistance—60 ohms; 60 multiplied by 60 equals 3600, and 60 plus 60 is 120; then dividing 3600 by

120, we have as a quotient 30 ohms, which is the required joint resistance.

Or we may divide the sum of the resistances by the square of the number of the circuits, thus: 6 circuits have a resistance of 60 ohms each; the sum of these resistances is, of course, 6 times 60, or 360, and the square of the number of circuits, that is, 6 multiplied by 6, is 36. Dividing 360 by 36, we find the result to be 10, which is obviously the joint resistance of the 6 circuits.

When the resistances of the circuits are unequal, the following plan must be adopted: If only two wires, we may divide the product of the resistances by their sum as before. If the joint resistance of more than two circuits be required, first find the joint resistance of any two of them, then, considering this as one resistance, combine it with a third, and so on.

Let us suppose that three wires have respectively the following resistances: 200, 300, and 100 ohms; we first take two of them; 200 and 300 multiplied together is equal to 60,000; 200 plus 300 is 500; dividing 60,000 by 500, we find the quotient to be 120 ohms, which is the joint resistance of the first two wires.

Calling that, now, one circuit, we multiply 120 by 100, the resistance of the third wire, finding the product to be 12,000; 120 added to 100 being 220,

which gives us as a result 54 and a fraction, this being the joint resistance of three circuits.

UNITS OF ELECTRICAL MEASUREMENT.

We have now seen that the batteries by which electricity is developed, the conductors by which it is transferred, the instruments by which it is made useful, and the electric current itself, have certain properties, magnitudes, or qualities, which it is often necessary to measure in order that their working value may be properly estimated.

That we may be able to make such measurements and to state their results, it is essential that we have some standard terms, or units, which, when expressed, convey to the mind definite ideas, precisely as in measuring a distance we would say so many feet or miles; or in expressing the flow of water, so many gallons per minute; or in describing the contents of a solid block, as so many cubic feet.

Furthermore, when one substance has several properties or magnitudes, a different system of measurement is required for each magnitude; for as in a cubic block of wood we should measure one of its sides by superficial measure, its contents by cubic measure, and its weight by still another system, and would state the result differently in each case, so the different electrical magnitudes each have their own units in which the results are expressed.

Sometimes we find that the results of certain measurements are obtained by reference to several different magnitudes; as, for example, when we time the speed of a horse, or a locomotive, we take the length of the distance traversed and the time consumed in traveling that distance, and thus calculate the velocity by reference to both length and time. In certain electrical measurements we find it necessary to resort to the same process, and combine different units to obtain a definite result.

Designations have been given to the practical electrical units from the names of distinguished electricians and scientists. The unit of electromotive force is called the "volt," from Volta; and the unit of resistance is called the "ohm," after Ohm, the German physicist and mathematician; while the unit of current strength is called the Ampére, from the French philosopher of that name.

THE VOLT.

The "volt" is the unit of E M F, and has very nearly the same value as a single cell of Daniell battery. Its precise value is .9268 of a Daniell cell in good condition; in other words, the Daniell cell is equal in E M F to one volt and seventy-nine thousandths—1.079.

The volt is equivalent to the electro-motive force required to produce a current of the strength of one

ampére in a circuit having a total resistance of one ohm.

The electro-motive force of most of the gravity batteries is almost the same as that of the Daniell, and the E M F of the Leclanche cell, is 1.481, or one volt, and four hundred and eighty-one thousandths.

THE OHM.

The standard unit of resistance, which we call the "ohm," may be defined as a resistance about equal to that offered by a wire of pure copper, one twentieth of an inch in diameter and two hundred and fifty feet long. Or it may be compared to one sixteenth of a mile of No. 9 galvanized iron wire; or to one mile of copper wire, No. 4½ Birmingham wire gauge, which is twenty-three hundredths of an inch, or nearly a quarter of an inch in diameter. It is also approximately equal to a piece of No. 35 copper wire, between 7 and 8 feet long. A mile of No. 12 galvanized iron wire has an average resistance of about 32 ohms.

The mark which may usually be found stamped on the base of a relay denotes the resistance of the coils from one binding screw to the other. If, for example, we have a relay marked 100 ohms, we know that that is the measured resistance of the

two spools, and that it is equal to about three miles of No. 12 galvanized iron wire.

THE AMPÉRE.

The unit of current strength was, until very lately, called a "weber," but is now called the Ampére; it may be defined as the strength of a current produced in a circuit having a total resistance of one ohm by an electro-motive force of one volt.

If, for example, we have a circuit consisting of one cell of battery, an electro-magnet, and the necessary connecting wires, as in the diagram Fig. 8, the battery, we will suppose, having an

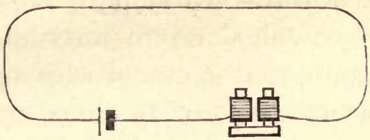

Figure 8.

E M F of one volt and an internal resistance of one third of an ohm, the electro-magnet and connecting wires also have resistances of one third of an ohm each, making a total resistance of one ohm in circuit.

The current flowing in this circuit will have a strength of one ampére. A mille-ampére is one thousandth of an ampére, and is made use of in computing currents of comparatively feeble strength.

OHM'S LAW.

We may now re-state Ohm's Law, giving specific values; thus:

The strength of current in ampéres flowing through a circuit is equal to the number of volts of electro-motive force divided by the number of ohms of resistance in the entire circuit.

The strength of current is ascertained by taking the E M F in volts, and dividing that number by the total resistance of the circuit, including that of the battery, wires, and instruments in ohms. The result will be in ampéres, or fractions thereof.

Let us see how this works out. A battery having an E M F of 50 volts, and an internal resistance of 75 ohms, is connected in circuit with a galvanometer having a resistance also of 75 ohms, and connecting wires having a resistance of 10 ohms. The total resistance in the circuit is that of the battery, galvanometer, and wire added together, *i. e.*, 160 ohms. To find the strength of current, we divide the 50 volts by the 160 ohms, which gives us a quotient of .3125 of an ampére, or 312½ milli-ampéres.

Therefore if we know the E M F and resistance of any circuit, we can easily figure out the strength of current. On the same principle, knowing the E M F in volts, of a battery and the current in ampéres produced thereby in a given circuit, we can

ascertain the resistance of that circuit, including that of the battery, by dividing the E M F by the current. Likewise, the value of the E M F may be obtained if we know that of the current, and of the total resistance of the circuit, for if we multiply the resistance in ohms by the current strength in ampéres, we find the value of the E M F in volts.

THE GALVANOMETER.

The galvanometer is an instrument for indicating the presence and direction of currents of electricity, and for measuring their strength.

One of its most important functions is the testing and measurement of the resistance of line wires, instrument coils, batteries, and insulation. It is also employed in detecting and localizing circuit troubles in telegraph and telephone lines, and in some cases such, for example, as the Atlantic cables, as a receiving instrument for telegraphic signals.

Its operation depends upon the action of the two forces—electricity and magnetism,—and, though galvanometers are made in many forms and are used in several different ways, they are all based on the fundamental fact that a magnetic needle is deflected,

or turned aside, from its natural position by the passage of a current of electricity in a conductor placed parallel to it.

When a steel needle is magnetized, and delicately pivoted at its centre, so that it is free to move horizontally, every one knows that it will set itself north and south; a common example being the ordinary compass needle.

This action of the needle is due to the influence of the earth, which is itself an enormously large and strong magnet. All magnets attract the opposite poles, and repel the similar poles of other magnets, and thus the north pole of the earth attracts the south pole of the magnetic needle, causing the needle to point north and south as it does.

It must not be forgotten that although we call the north pointing pole of the needle, the north pole, it is certainly the pole of opposite character to the north pole of the earth, and therefore, speaking correctly, we should call it the south pole, and the French do so call it. We, however, have become accustomed to call it "north," simply because it points to, or seeks the north; and we shall probably continue so to call it, being a people of steady habits. It will be properly expressed if we strike a mean between the two, and call it the north-seeking or north-pointing pole. Of course, these remarks may be equally applied to the south-seeking pole.

If we forcibly turn the needle from its north and south position to a new position, pointing east and west, as soon as we remove the force, back it goes to the north and south position again.

Thus we see that the magnetism of the earth exercises a constant force on the needle, tending to keep it pointing north and south.

In 1802, Romagnesi, a physicist of Trente, in Italy, discovered that a current of electricity affects a magnetized needle, and causes it to turn from its usual position. He, however, took no great pains to publish his discovery, and it was neglected and soon dropped into oblivion.

In 1819, Oersted, of Copenhagen, ascertained that if a wire conveying an electric current, be placed parallel to a magnetic needle, the needle is drawn away from its position pointing north and south, and tends to set itself in a new position at right angles to the electric wire.

The amount of deflection depends to a certain extent upon the strength of the current, and the direction of the deflection depends upon the direction of the current. If the electric wire is above the needle, and the direction of the current is from north to south, the needle will tend to point eastwardly. Leaving the wire still above the needle, and changing the direction of the current so that now it flows from south to north, we find that the

north end of the needle now deflects in a western direction.

If we now change the wire to a position *under* the needle, we find all the motions to be reversed; for passing a current from north to south, the needle now exhibits an inclination to turn to the west, while if we pass the current from south to north, the needle has an eastward inclination.

It should be here explained that when we speak of the deflection of a needle, the north end of the needle is uniformly the one referred to, the south end of course moving oppositely.

We may readily understand the reason for these movements, and why they should occur. We have already indicated the cause of the natural inclination of the magnetized needle to place itself in a position pointing north and south, to be the attraction of a much stronger magnet—the earth,—and we may easily believe that an unseen force which causes the needle to point away from the north, must also be of a magnetic character; and so it proves to be, and the reason of the deflection is as follows:

A wire carrying electricity, becomes practically itself a magnet; that is, a straight current produces in a wire, a magnetic field. This any one may easily prove for himself, by passing an electrical current through a wire of iron, copper, brass, or any other metal, and permitting the wire to dip into a heap of

iron filings. The filings will instantly cling to the wire, and all round it, just as if it was a natural magnet. The electric wire having thus virtually been transformed into a magnet, when placed beside the magnetic needle, interferes with the attraction of the earth, and pulls the magnetic needle to one side.

The case is simply a very weak but very near magnet, *i. e.*, the current-carrying wire acting on a poised magnetic needle in opposition to a very strong but very distant magnetic pole—the north pole of the earth ; and thus the needle, being acted upon by both oppositely, takes up a halfway position, as it were, "on the fence." The earth's magnetism tends to make the needle point north and south ; the electric current acting on the needle tends to make it assume a position pointing east and west. The resultant force will of course be between the two, and will depend on their relative strength. If the current is very strong, the needle will turn a long way round, but never farther than to a complete right angle.

But we have so far, only considered the effect of one parallel wire. If we want a greater deflection, and our battery power cannot conveniently be increased, what is to be done?

If we cannot increase the battery, we can increase its power of acting upon the needle, by using a

parallel wire on both sides of the needle; for if we carry our conducting wire, first over the needle from north to south, and then back from south to north under the needle, the effect will be doubled. If the wire, instead of making only one such convolution round the needle, were to make two, the force would again be doubled; and if several convolutions are wound round the needle, the force would be increased nearly in proportion to the number of convolutions; we say nearly, because the current is itself weakened by the additional length of wire required.

If the convolutions are greatly multiplied, so as to form a coil, the force is enormously increased, and we have what the first constructor of the galvanometer called a "multiplier."

All galvanometers, therefore, consist of a coil of insulated wire, and a magnetic needle delicately suspended in such a position as to be easily deflected by the passage of a current of electricity through the coil. These, with the addition of a dial plate, graduated so that the movements of the needle may be interpreted, are the only absolutely essential features of the instrument.

The galvanometer was one of the earliest results of Oersted's discovery; it was, indeed, in the same year, 1820, that the first galvanometer was invented by Professor Johann S. C. Schweigger, of Halle,

who passed a number of turns of insulated wire round a compass needle, thus multiplying the effect of the electricity, and constructing a galvanometer.

An instrument of this rudimentary character is shown in Figure 9.

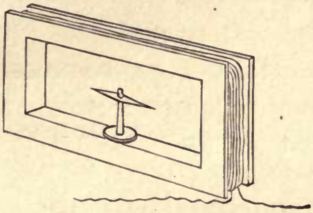

Figure 9.

Although the ordinary galvanometer constructed as above, is very well adapted to detect the presence or indicate the direction of a current, and for some simple measurements, especially for those in which the deflection is not greater than fifteen or twenty degrees, it is not to be depended upon for any testing in which a greater deflection is produced, for the following reason: that when a needle is deflected, it is not in the same position in its coil as when at zero; the greater the deflection, the farther is the needle moved away from the position where its coil most powerfully influences it, and the nearer the needle approaches the right angle, at which point the coil has no influence on it at all, the weaker does the action of the current become. In

order to overcome this difficulty, and for other mathematical reasons, galvanometers have been invented in which the tangent, or sine, of the angle of deflection is proportional to the strength of current measured. These are called tangent, or sine galvanometers.

THE TANGENT GALVANOMETER.

The tangent galvanometer consists, broadly speaking, of a ring having a groove on its edge filled with insulated wire, and provided with a needle which must not be longer than one sixth of the diameter of the ring, hung or pivoted precisely in its center, as shown in Figure 10.

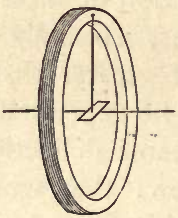

Figure 10.

One of the best tangent galvanometers is that known as the "Western Union Standard," as made by J. H. Bunnell & Co., of New York.

This instrument is mounted on a circular hard-rubber base, 7⅜ inches diameter, provided with

levelling screws and anchoring points. The Galvanometer consists of a magnetized needle ⅞ inches in length, suspended at the center of a rubber ring 6 inches in diameter, containing the coils. The coils are five in number, of the resistances, 0, 1, 10, 50, and 150 ohms. The first is a stout copper band of inappreciable resistance; the others are of different sized copper wires carefully insulated. Five terminals are provided, the plug holes of which are marked respectively 0, 1, 10, 50, and 200.

The ends of the coils are so arranged that the plug inserted at the terminal marked 200, puts in circuit all the coils; at the terminal marked 50, all except the 150 ohm coil; and so on, till at the zero terminal only the copper band is in circuit.

Fixed to the needle, which is balanced on jewel and point, is an aluminum pointer at right angles, extending across a 5-inch dial immediately beneath. On one side, the dial is divided into degrees; on the other it is graduated, the figures of the scale corresponding to the tangent of the angles of deflection.

The needle is sometimes suspended by a fibre of silk, and, of course, can be readily provided with coils wound to any required resistance.

The instrument is made complete and convenient by being provided with a mahogany case, and a

strap for carrying it. This instrument is shown in Figure 11.

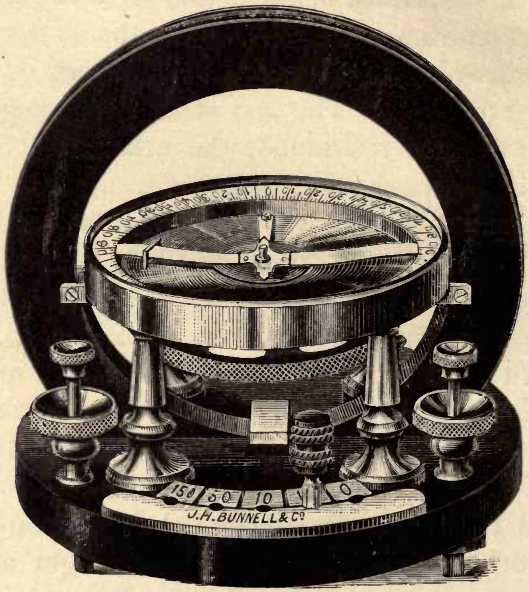

Figure 11.

When this instrument is used to measure currents, the strength of the current is proportional to the tangent of the angle of deflection.

For the benefit of the non-mathematical experimenter, we may explain that a tangent is a line drawn at right angles to one of the diameters of any circle, and touching the circumference, as in Figure 12, A D is a tangent to the circle B C E F.

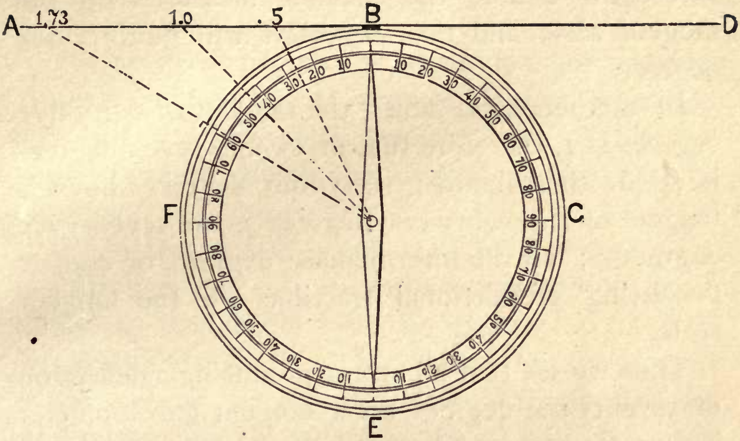

Figure 12.

In the case of the tangent galvanometer the dial of the instrument is the given circle, and the zero point is the point at which the tangent touches the circle. The tangent is, therefore, an imaginary line, which must be parallel to that diameter which connects the degree of ninety on one side to the same degree on the other side, and at right angles to the diameter or line connecting the two zero points. Let us suppose that the circle is the dial of a galvanometer marked off into degrees, and that the needle, by a given current, is deflected to twenty-seven degrees; double the current strength will not double the deflection, making fifty-four degrees, but will produce a deflection which, carried out,

will show double the distance measured on the tangent scale, and that deflection will be forty-five degrees.

In mathematical tables, the tangent of forty-five degrees is 1, therefore that of twenty-seven degrees is .5, or thereabouts; sixty-four degrees shows a tangent of 2, seventy-two degrees 3, and seventy-six degrees 4; all the intermediate degrees, of course, producing proportional fractions on the tangent scale.

Thus we see that a current producing a deflection of seventy-six degrees on a tangent galvanometer is just four times as strong as a current producing a deflection of forty-five degrees on the same galvanometer. If a tangent galvanometer is graduated to degrees only, when it is used, to obtain correct results, we must reduce the degrees to tangents by means of a table of tangents. A tangent and sine table will be found at the end of this book for reference in such cases.

Some of the best tangent galvanometers now made—for example, the one we have described—have their dials graduated in addition to the degrees, with a scale corresponding to the tangent divisions.

THE SINE GALVANOMETER,

Is one in which the coils are made moveable, so

as to be capable of revolving on the axis, around which the needle turns.

The needle is pivoted, or suspended, horizontally. A scale graduated with degrees is attached to the coil and a pointer fixed on the base, so that the angle through which the coil is turned can be observed.

When the needle is deflected by a current passing through the coil, the coils are turned by hand, following the needle in its deflection; as the coils are thus turned, they, of course, maintain their power on the needle, and it accordingly diverges still more, but the angle it makes with the coils becomes less and less, until at length a point is attained at which the needle remains parallel with the coil.

When this point is reached, the influence of the earth's magnetism exactly balances the deflective force of the current. The strength of the current that produces the deflection will then be directly proportional to the sine of the angle through which the coil is turned.

As shown in Figure 13, the sine of any number of degrees is that part of the diameter of a circle which is included between a line drawn from the center to the zero point of the graduation circle, and another line parallel to the first, cutting the circle at the degree whose sine is required.

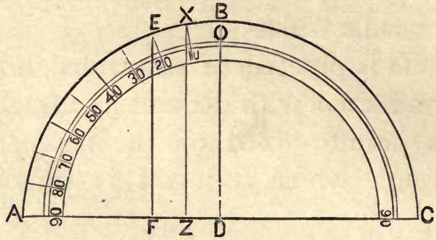

Figure 13.

Thus, in the figure, A B C is a semi-circle which we may suppose to be the graduated scale of a sine galvanometer. B D is the line from the center to the zero point, and X Z and E F are parallel lines cutting the circle respectively at ten and twenty degrees, the space on the diameter A C between Z and D being the sine of ten degrees, and the space between F and D the sine of twenty degrees.

The sine of ninety degrees, or a right angle, is in sine tables called 1000, that of one degree 17, and the sines of all degrees between 1 and ninety, will be found in the table at the end of this book.

If a current of known strength, then, deflects the needle to an angle of thirty degrees, and the current to be compared deflects the needle to angle of forty-five degrees, the strength of the second current is to the first as the sine of forty-five degrees is to the sine of thirty degrees.

It is customary, as in the use of the tangent

galvanometer, to read off the degree, and refer to a table of sines for the required sine.

The sine galvanometer is not so convenient for general use as the tangent galvanometer, and is consequently but little used, except for scientific experiments and for measuring and comparing weak currents.

THOMSON'S REFLECTING GALVANOMETER,

Is the most sensitive galvanometer known, and is very useful in measuring very high resistances, such as the insulation of cables.

Its moving parts are very light and small, the needle being a little piece of watch spring about a quarter of an inch long. This is suspended by a silk fibre in the center of a coil consisting of a great number of turns of wire.

Instead of fastening a pointer to the needle, as in ordinary galvanometers, the indications are made by attaching a mirror about the size of a silver five cent piece to the needle. A graduated scale is placed two or three feet from the mirror, and a beam of light derived from the reflection of a lamp by the mirror shines upon the scale, which is usually graduated to 360 divisions on either side of the zero point, which is in the center of the scale.

Whenever the needle moves, the beam of light, of course, moves with it, and is thus equivalent to

an index needle of great length and of no weight, and a very small movement of the needle produces a considerable movement of the spot of light on the scale.

The coil completely surrounds the needle so that the needle is always under its influence irrespective of its angle of deflection.

This galvanometer is often made astatic, and is extremely accurate as well as extremely sensitive. The infinitesimal current developed by dipping a brass pin and a steel needle into a drop of salt water, will, when the needle and pin are connected by wires with the galvanometer terminals, send the spot of light swinging across the scale.

The coils are sometimes wound with German silver wire, in order that the resistance may be little affected by changes of temperature; the increased resistance of German silver over copper being of no consequence when the instrument is used to measure high resistances.

The resistance of a Thomson galvanometer so wound is sometimes as high as 50,000 ohms, and such an instrument with but one cell of Daniell battery would give a large deflection through ten million ohms.

ASTATIC GALVANOMETERS.

There are two ways of increasing the sensitiveness of a galvanometer. The first method, which

consists in increasing the effective action of the current by coiling a great many convolutions of the insulated conducting wire round the needle, we have already considered. The second method is to decrease the opposing influence of the earth's magnetism which tends to keep the needle pointing north and south.

It is very clear that unless this is done, the current has to keep up a constant fight against the power of the earth's directive action on the needle. Therefore it is also clear that if we can neutralize that force in the earth's magnetism, which tends to keep the needle pointing north and south, the current will have so much more force to exert on the needle, and will consequently be able to deflect the needle much easier. We can do this by placing two magnetized needles on one axis (which may be a light wire of brass or aluminum), with their poles placed oppositely, the north pole of one over the south pole of the other, and *vice versa*, as in Figure 14.

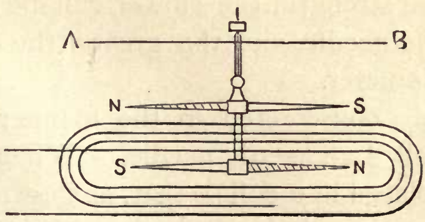

Figure 14.

When such a combination is used, the earth will attract the upper needle and tend to keep its N pole pointing northward ; but it will repel the lower needle with an equal force, and tend to make it turn completely round. Thus the magnets so arranged have very little tendency to place themselves north and south, because the force acting on one is directly counterbalanced by the force acting on the other.

If the two needles were exactly equal in power, they would have no tendency to point in any particular direction, for any directive action in one will be counteracted by an exactly equal and opposite action in the other. In practice, one needle is made a little stronger than the other, so that the pair has sufficient tendency to point north and south to enable it to regain its position after having been deflected.

On the same axis with the needles we may place a pointer, A B, to denote the deflections.

The nearer the two needles are to one another, in magnetic strength, the slower will be the vibrations of the needle, and the greater the delicacy of the galvanometer.

A needle constructed in the manner described above is called an astatic needle. When an astatic needle is placed in a coil so that, as shown in Figure 14, the lower needle is within the coil and the upper

one above it, its deflections will be much greater than if an ordinary needle were used, for two reasons: in the first place, the power which keeps the needle in its fixed position is small, and the needle is consequently more easily influenced; in the second place, the force of the coil is exerted in the same direction on two needles instead of one, for the upper needle being much nearer the upper part of the coil than the lower, is deflected by it alone, and the deflection so induced is in the same direction as that of the lower needle.

An astatic needle so mounted in a coil constitutes an astatic galvanometer.

THE DIFFERENTIAL GALVANOMETER

Is one which has a needle poised or suspended like that of the tangent or sine galvanometers, but, unlike them, the needle is acted upon by two coils of equal length and resistance, insulated from one another with great care. These coils each surround the needle with an equal number of convolutions, which in each wire are equidistant from it.

When this galvanometer is used, one end of each coil is connected with one pole of the battery, and the other end of each coil with a wire leading to the other pole of the battery in such a way that the current flows in opposite directions through the two wires. Now, if the current in both coils is of the

same strength, one tends to deflect the needle to the right and the other to the left, and the needle being pulled with equal force in both directions, remains at rest.

If, now, one current be made stronger than the other, the balance will be destroyed, and the needle can be moved by the stronger current.

If we wish to measure an unknown resistance with this galvanometer, we insert the resistance to be measured in the circuit of one of the coils. This, of course, weakens the current in that coil, and consequently its effect on the needle, which no longer remains balanced, but deflects to one side. If we now insert a rheostat in the other side, and unplug resistance until the needle again balances or comes to zero, we know that the current in each coil must again be equal, and, therefore, that the unknown resistance in the circuit of one coil must be exactly equal to the resistance unplugged from the rheostat.

SHUNTS.

Although shunts are rarely necessary in ordinary measurements, at least, when the tangent galvanometer or Wheatstone Bridge systems are employed, any treatise on the galvanometer would be so manifestly incomplete if they were not noticed, that we regard it as eminently proper to devote a short space to them and their uses, the more especially as

experimenters, and other persons making frequent measurements, may occasionally desire to prepare shunts for themselves.

When the differential galvanometer is used, the shunt is almost an essential, and it is also useful in such direct measurements where the deflection of the needle would be so great as to be untrustworthy.

A shunt may be defined as a contrivance for leading by another route part of the current which, as a whole, is too powerful for the immediate purpose. In the present connection, it is a coil of wire used to divert some definite proportion of a current aside from, or past the galvanometer, instead of allowing it to pass through the galvanometer coils. For example, if the galvanometer has its two terminals united by a wire having a resistance equalling one ninety-ninth of the galvanometer resistance, we reduce the galvanometer to one hundredth of its original sensibility, ninety-nine hundredths of the current passing through the shunt and the remaining 100 through the galvanometer.

Similarly, if the shunt be exactly equal to the galvanometer, the current will divide in equal proportions between the galvanometer and the shunt. If the shunt is one half the resistance of the galvanometer, two thirds of the current will pass through the shunt and one third through the galvanometer, and so on.

The rule is, that the current divides between the galvanometer and the shunt, in inverse proportion to their respective resistances, the greater portion of the current always going through the smaller resistance, and the smaller portion through the greater resistance.

Galvanometers requiring shunts are usually provided with three, which are respectively one ninth, one ninety-ninth, and one 999th.

These reduce the amount of current passing through the galvanometer, respectively to its one tenth, one hundredth, or one thousandth part.

The formula for finding what the resistance of a shunt should be to give it a definite value, is to make the resistance of the shunt equal to that of the galvanometer, divided by the multiplying power required, minus one. For example: Suppose we have a galvanometer whose resistance is 100 ohms, and we wish to prepare a shunt which will reduce the sensitiveness to one tenth; we divide the galvanometer resistance by the fractional part to which we desire to reduce the sensibility, minus one; that is, we divide the 100 by 10 minus 1, which is of course 9. The quotient of 100 ohms divided by 9 is 11 ohms and one ninth, which is the resistance of the required shunt, and is one ninth of the resistance of the galvanometer. This is called a shunt, having a multiplying power of 10.

To obtain the true value of a deflection taken from a shunted tangent galvanometer, we have to multiply the tangent by the multiplying power of the shunt used. To ascertain the multiplying power of any shunt whose resistance is known, we divide the resistance of the galvanometer by the resistance of the shunt, and add one to the quotient. For example: we are using a galvanometer with a resistance of 100 ohms, and we insert a shunt whose resistance we know to be 25 ohms; to find out by what number we have to multiply the shunted result, we divide the 100 by 25, which gives us a quotient of 4, to which must be added 1, showing that 5 is the multiplying power required.

It is proper to state that when we use a shunt, the current which passes through the galvanometer is not strictly the proportionate part of the original current to which it is apparently reduced, because by the act of employing the shunt we furnish a double route for the current, and thereby diminish the external resistance of the circuit, and, as a consequence, the strength of current furnished by the battery is increased. It is, therefore, the increased current instead of the original one that splits between the shunt and the galvanometer.

To illustrate: If we are using a tangent galvanometer, and the tangent of deflection without the shunt is .80, we would naturally have supposed that

C. L. Cory

on the introduction of a shunt which reduces the sensitiveness of the galvanometer one half, the tangent would also be brought down one half, that is to .40. But such is not the case, the result being some higher tangent than .40; and to bring about an accurate result, we must first find the joint resistance of the shunt and galvanometer, and then insert an additional resistance in the battery circuit equal to the amount by which the original resistance was decreased. Thus, if both the galvanometer and shunt are 100 ohms resistance, the joint resistance of the two is 50 ohms.

In this case, therefore, we should have to insert 50 ohms in the battery circuit, to compensate for the decrease in resistance, and to bring the current back to its original strength.

RHEOSTATS AND RESISTANCE COILS.

The name Rheostat was originally given by Wheatstone, to an instrument which he devised for the purpose of varying at will the amount of resistance in a circuit.

It consisted of two cylinders of equal diameter, one of brass and the other made of some non-conducting material. These were fixed near each other, and a fine German silver wire was wound in opposite directions round the cylinders, its ends

being in electrical connection with the metallic axes of the cylinders.

The axes of the cylinders were connected with two binding screws by means of sliding contacts. The part of the wire which does not lie on the metal cylinder is the only part that produces resistance between the binding screws, and by winding the wire from one cylinder to the other, resistance could be added to or taken from the circuit. This apparatus is scarcely ever now used, but its name survives, and is now often applied to a set of standard resistance coils, arranged together in a box, and adapted for use in electrical measurements.

What we now call a rheostat, is a box containing a number of spools filled with insulated wire, the resistance of the wire on each spool being equal to some multiple or sub-multiple of the ohm, the unit of resistance. The several coils are arranged as in the figure.

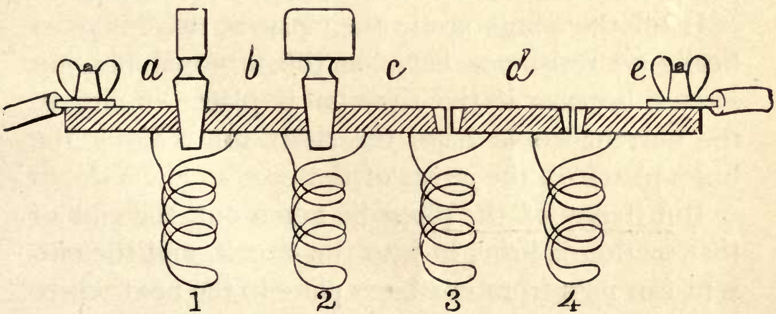

Figure 15.

The cover of the box is generally of hard rubber, and a series of connecting pieces of brass, *a*, *b*, *c*, are placed on it. The ends of the several brass pieces are very close together, but do not touch, and holes are bored between the ends for the insertion of brass plugs with hard rubber handles, so that when all the plugs are inserted, there is an unbroken line of conducting brass plates all along the cover of the box.

Binding screws are fixed to the ends, so that any desired connections can be made. Each of the coils in the box below has its terminals united to two of the plates, as in the figure, coil 1 is attached to the plates *a* and *b*, coil 2 to *b* and *c*, so that every coil joins one of the brass plates to the next.

The different coils may be of any required resistance, and may be varied indefinitely. They are usually made to increase consecutively, as for example, 1, 2, 5, 10, 20, 50, 100, 500 ohms, and so on.

If all the plugs are in their places, there is practically no resistance between the terminal binding screws, because if the rheostat is placed in circuit, the current would have the short route along the brass plates on the cover of the box.

But if any of the plugs be taken out, the coil of that section is brought into the circuit, and the current can pass from one brass plate to the next where the plug is withdrawn only by traversing the coil

thus introduced into its path, and just so much resistance as is represented by that coil, is added to the entire resistance of the circuit.

Thus, if the coils shown in the figure have respectively 5, 10, 25 and 100 ohms, and the plug between *b* and *c* be withdrawn, 25 ohms resistance is thereby thrown into the circuit between the binding screws.

We see, then, that by withdrawing any or all of the plugs, we can introduce less or more resistance.

Numbers representing the various resistances of the coils are usually placed opposite the holes, and by adding together the numbers unplugged, we ascertain the total resistance inserted.

The wire used in resistance coils is generally made of German silver, because the resistance of that alloy changes very little with variation of temperature; it is insulated with silk, and always wound double, as shown, so as to neutralize any inductive action of the convolutions on each other, and also to prevent the coils from affecting galvanometers near them; when so arranged, the current flows at the same time in two opposite directions round the spool, effectually preventing any inductive troubles. After the spools are wound and correctly proportioned, they are saturated with hot paraffine, by which their insulation is maintained, and dampness prevented.

Thick wire is generally used for the small resistances, and fine wire for the higher ones.

It is usual to so arrange the different resistances, that by properly combining them, any value, from a fraction of an ohm to 10,000 ohms, can be obtained.

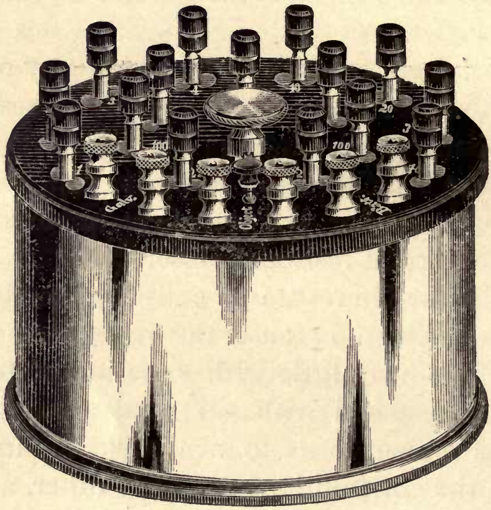

Figure 16.

The resistance box can be of any suitable shape, and in the figure a circular box of coils is shown. When so made, it is very convenient to pack in a box with the galvonometer, for conveyance from place to place.

THE WHEASTONE BRIDGE.

The Wheatstone Bridge, or balance, though usually classed with, and explained in connection with galvanometers, is, strictly speaking, not a galvanometer, but a system of measurement; or an arrangement of circuits whereby a galvanometer may be most advantageously employed.

It will doubtless be a surprise to some, to hear that Wheatstone's bridge was not the invention of Wheatstone. Such however is the case; it was invented by Mr. S. Hunter Christie, who described it before the Royal Society of London, in 1833, in which year he also published a paper regarding it, in the Philosophical Transactions. He called it a "differential arrangement" and used it for measuring the relative conduction of different metals, and also as a means for discovering the conducting power of metals at different temperatures.

Notwithstanding all Mr. Christie's efforts to make his invention known, it remained in oblivion, until again brought forward by Sir Charles Wheatstone, who in 1843, ten years later, wrote an important paper on electrical measurement, stating the source from which the instrument was derived, and giving Christie's dates of invention, and publication.

It was, therefore, from no fault of Wheatstone, that his name has become inseparately coupled with that of the bridge, since he did his best to ascribe

due credit therefore to Christie, who unfortunately was ten years too early to be appreciated.

Even Wheatstone, however, made no attempt to use variable resistances in the two arms, he always using equal resistances, and consequently having his limit of measurement greatly circumscribed.

Werner Siemens, in 1847, was the first to construct a bridge with arms provided with variable resistances, thereby largely amplifying the range of the instrument.

We will here describe the construction of the bridge, and afterwards attempt to elucidate the principle of its operation.

Figure 17 shows the theoretical arrangement of a

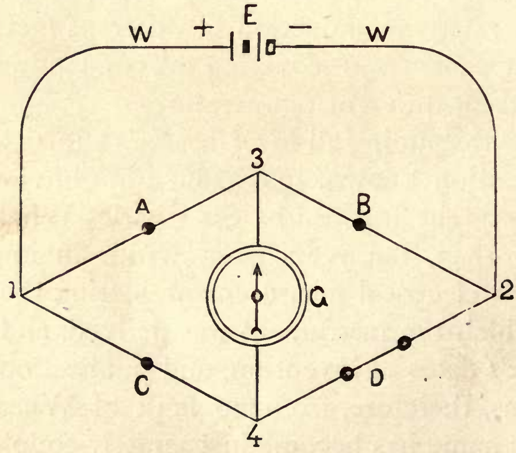

Figure 17.

Bridge system, consisting of a lozenge-shaped, four-sided figure, two of its corners, 1 and 2, being united by the wires W to the two poles of a battery, and the two other corners, 3 and 4, connected by a cross wire and galvanometer G.

This was the original form of the balance; but in practice it is rarely now so constructed, but is arranged usually in a more suitable form for actual work.

Yet it is very convenient in describing the bridge to use the lozenge form, because it is a figure readily borne in mind, and with it, the principles involved are easier of explanation.

Referring to the diagram, we see that a current of electricity starting from the positive pole of the battery, on arriving at the point 1, has two paths before it; one by C, 4, D and 2, the other by A, 3, B and 2, both routes re-uniting at the point 2, and thence proceeding by wire W to the negative pole of the battery, thus completing the circuit.

These parallel routes are called the branches, arms, or sides of the bridge.

The current therefore divides at 1, and if the resistances of each path are equal, as we may for the present assume they are, half of the current goes by A B, and the other half by C D, to the point 2, and from that point, the two currents go together back to the battery. Now, whatever the resistances of

the lines A B and C D may be, so long as they are equal to one another; that is, so long as A B is equal to C D, the galvanometer G will not be affected in any way; its needle will not be deflected, although it is, as we see, connected with both lines by a cross wire.

Let us suppose that A and C each have a resistance of 10, and B and D each a resistance of 30 ohms; which will of course be equivalent to a total resistance of 40 ohms on each side; there will in this case be no deflection of the galvanometer needle, because A B is equal to C D, both having the same resistance.

Repetition

Furthermore, when A bears the same proportion to B, that C does to D; or when A bears the same proportion to C, that B does to D; or when A multiplied by D is equal to C multiplied by B, no current will pass through the cross wire, and there will be no deflection of the needle.

If we suppose A to have a resistance of 10, B of 200, C of 100, and D of 2000 ohms, the above conditions are fulfilled; for 10 is to 200 as 100 is to 2000; and 10 bears the same proportion to 100, as 200 does to 2000; moreover 10 multiplied by 2000 is equal to the product of 200 multiplied by 100.

With these resistances, therefore, the proper proportion exists, balance is established, and no deflection of the needle is produced.

We thus see from the above, that if we know three of the resistances, we may easily find the fourth; and that it is by the proportion subsisting between the resistances of the arms of the bridge, that the resistance of the fourth can be calculated, when the resistances of the other three are known.

If we have known resistances at A and C, a rheostat or adjustable resistance box in the branch B, and the object to be measured, or unknown resistance in D, and then vary the resistance in B, until the needle comes to zero, we may be sure that the unknown resistance in D bears the same proportion to that unplugged in the rheostat B, that the resistance of C does to that in A.

This of course is readily calculated by simple proportion or the "rule of three."

We will presently see why this should be so. It has already been stated, (page 11) that an electrical current, or a steady and constant transfer of electricity between any two points, is caused by a difference of potential between such points. We have seen that if we connect the two poles of a battery by a long wire, such as a telegraph line, the potential will fall regularly and gradually from the end which is united to the copper or positive pole of the battery; and will rise regularly and gradually from the end which is attached to the zinc or negative pole, until they both meet in the middle of the line, where the potential is zero.

We have also stated that if instead of connecting the poles of the battery by a metallic conductor, we put one pole, say, the negative to a ground wire, and attach the other to a linewire or other resistance connected with the earth at a distant point, so that a steady current flows through the wire to earth, the potential will fall regularly through the resistance of the line, from its highest figure at the junction of the line with the positive battery pole, to zero at the distant ground end.

It is very evident from the above that if a current is, as we have said, caused by a difference of potential between two points, there can be no current between two points which are of the same potential, because there is no force tending to produce one. Just as we may, after stating that steam is produced by heating water to a certain temperature, go on to show that if the water is not heated, steam cannot be produced.

To apply the idea to the Wheatstone Bridge, let us consider the construction and arrangement of the bridge circuits.

A conducting wire attached to the positive pole of a battery E (Fig. 17), is extended to a point 1, where it splits into two conducting wires, A B and C D.

These wires traverse different routes, and re-unite at a point 2, and from the point 2 a wire proceeds to the negative pole of the battery E.

It is obvious that the peculiar form of the arrangement is not essential: the main point being that the circuit must always be split at some point into two branches, which at some other point are again united.

Now the potential must certainly at the point 1, where the circuit splits, be the same for both wires; and as certainly at the point 2, where the wires reunite, the potential must also be the same for both wires; and if the resistances of the two branches A B and C D are equal, the fall of potential will go on just as if the two wires were one, and will therefore be equal at any two points equally distant in resistance from the point 1; consequently, whatever the potential is at the point 3 in A B, it likewise is at the point 4 in C D, and when we unite those points by a cross wire and galvanometer, no current passes between them, and no deflection of the needle can occur.

Nor could there be any current in a bridge wire connecting the points A and C, or B and D, because their potentials also are equal. But if we connect A and D, or C and B, by a cross wire or bridge, the needle of the galvanometer in the bridge will deflect violently, because A is much nearer than D to the point 1, as also C is much nearer than B, and the difference of potential naturally causes a current between the two points, flowing through the galvanometer.

Let us see now, what will happen, if the resistances of the branches A B and C D are unequal. If A bears the same proportion to C, that B does to D, no current will pass between 3 and 4; for still, the potential is the same for both branches, at the terminal points 1 and 2, and no matter what the resistances are, between those points, if any two points, such as 3 and 4, stand at the same proportion of their respective resistances from the point 1, the potential of those points must be the same, and, therefore, no current can flow in a cross wire connecting them.

To illustrate: let us suppose that the point 1, connected with the positive pole of the battery has a potential of 20 plus, and the point 2, connected with the other pole, a potential of 20 minus, making a total difference of 40 between the two points. In this case we assume the two branches to be equal, each having a resistance of 100 ohms. Let 3 and 4 be points exactly in the center of each resistance, so that the resistance between 3 and A is 50 ohms, and the resistance between 3 and B is also 50 ohms, the same being true of 4 and C, and 4 and D. The potential of the points 3 and 4 is, of course, a figure just halfway between that of 1 and that of 2, viz: zero; and no current can pass through the galvanometer, because there is no difference of potential between the points 3 and 4.

Let A and C be exactly halfway in resistance between 3 and 1, and 4 and 1; that is, the resistances between 1 and A, and between 1 and C, are each 25 ohms; the potential at those points must be of course just one fourth of the total difference, *i. e.*, 10 plus; again, both points being equal, there can be no current in a cross wire connecting them.

Now let B and D be exactly halfway in resistance between 3 and 2 and 4 and 2, (their respective potentials thus being 10 minus,) and connect A and D by a cross wire and galvanometer: these potentials are not equal, that of A being 10 plus, and that of D 10 minus, a total difference of 20; therefore a current flows and the needle deflects. If the branches are not equal, for example, if A has a resistance of 10, B of 100, C of 20, and D of 200, the total resistance in A B thus being 110, and in C D 220, one third of the current will pass through C D, and two thirds through A B. Yet the difference of potential is the same between 1 and 2, and must necessarily fall along the two branches exactly as before, so that as there is between 1 and 3 a resistance of 10 ohms, being one eleventh of the entire resistance A B, and between 1 and 4, a resistance of 20 ohms, that is, one eleventh of the total resistance C D, the potential 20 plus at the point 1, must at the points 3 and 4 have fallen in the same proportion, one eleventh of the difference between 20 plus and 20 minus, and

the potentials at 3 and 4 are equal; therfore, no current passes between those points, and the needle in the bridge wire does not deflect.

The principle is, we see, that of balancing potentials against one another, without any reference to the strength of current passing, and when we try to understand it, without loading it down with two volumes of algebraic equations and differential calculus, it is really not at all difficult of comprehension.

COMPARISON OF DIFFERENT SYSTEMS OF MEASUREMENT.

There are three principal methods of measuring resistances, and of testing lines. These are: First, by the angles of deflection of the galvanometer needle. Second, by matching with a differential galvanometer the resistances to be measured with other and known resistances, until the needle of the galvanometer shows no deflection. Third, by the Wheatstone Bridge, or Balance.

We may use the first general method in two ways,—the first of these sub-methods being that of substitution, which is the simplest plan in use. Any good galvanometer may be used when this plan is adopted.

It consists in placing the galvanometer and battery in circuit with the resistance to be measured, taking

note of the amount or number of degrees of deflection, and then replacing the unknown resistance by a known resistance, for example a rheostat, and adjusting the number of ohms in the rheostat, till the deflection of the needle is the same as before.

The unknown resistance is then about equal to the known resistance by which it has been replaced.

The second of these sub-methods requires a sine or tangent galvanometer.

It consists in comparing the relative strength of current, produced by the same battery in two circuits, of which one has a known resistance, while the other includes the resistance to be measured.

When this plan is followed it is requisite, either that we know the resistance of the galvanometer and battery; or that those resistances must be so small in proportion to the remainder of the circuit, that they can be neglected without greatly affecting the result.

In using this method we may, to illustrate, place a tangent galvanometer having a resistance of 100 ohms, a battery having a resistance of 10 ohms, and some known resistance, say 100 ohms, in circuit together, and find the deflection to be, let us say 35 degrees. Then we take the known resistance, 100 ohms, out of circuit, and substitute the resistance to be measured, finding the deflection to be altered, say to 25 degrees.

We have already seen that the strength of current passing through a tangent galvanometer is always proportional to the tangent of the angle of the needle's deflection; and we also know that it is inversely proportional to the resistance in circuit, that is, the current increases as the resistance decreases, and *vice versa.*

Therefore we refer to our table of tangents, finding the tangent of 35 degrees to be .700 and that of 25 degrees to be .466; the strength of current then may be calculated by direct proportion, tangent .700 being to the strength of current, when the known resistance, 100 ohms, was in circuit, as tangent .466 is to the current strength when the unknown resistance was substituted therefore.

The unknown resistance is calculated by inverse proportion, tangent .466 being to tangent .700 as 210 ohms, the total original resistance, is to the total resistance in circuit when the unknown resistance is substituted for the 100 ohms, viz: in whole numbers 315 ohms.

Deducting from this the resistance of the galvanometer and battery, *i. e.,* 110 ohms, the unknown resistance proves to be 205 ohms.

For several reasons, measurements by the deflection angles cannot be depended upon, when great accuracy is required.

The principal reason is that the electromotive

force and internal resistance of the battery is very apt to vary during the time of making the measurements. It is also sometimes inconvenient to have to make the necessary deductions of battery and galvanometer resistances, particularly when we do not know them.

When the differential galvanometer, or Wheatstone Bridge, are used, such defects and inconveniences are obviated, and systems of measurement in which these instruments are employed, are called "null" methods, because the results are obtained by the absence, instead of by the amount of deflection; the Wheatstone Bridge going a little further than the differential, and giving its result, not only by absence of deflection, but also by absence of current.

It is clear that changes in the battery cannot affect the result in the differential galvanometer, because as the current goes round the needle simultaneously, in both directions, any change would act in both coils, and being thus neutralized, will exercise no effect on the needle.

If the differential galvanometer were as perfect practically, as it is theoretically, it would be a most accurate instrument, but in practice it is found to be very difficult to adjust the two halves of the coil, so as to have exactly equal effects on the needle; moreover, imperfect insulation between the coils sometimes occurs.

The differential galvanometer has therefore been found to be by no means a perfect practical instrument, and it has consequently been in a great measure superseded by the Bridge, which has none of the foregoing defects, and which, for the same bulk and cost, has far greater accuracy and sensibility within wide limits than the differential galvanometer.

The Wheatstone Bridge has proved to be in every respect the most successful way of measuring resistance.

Its advantages lie in its accuracy, and in the simplicity of its operation; and in the fact that no special form of galvanometer is required. Any good galvanometer may be used with the bridge; it need not even be graduated; all that is necessary is that it shall be sensitive enough to detect the presence, and show the direction of a current, without in any way determining its value, or comparing its value with that of another current.

The apparatus of the Wheatstone bridge has heretofore usually been of an expensive and cumbrous character, and has thus been beyond the reach of the rank and file of our American electricians, operators, and inspectors, who are not, as a general thing, rolling in wealth.

An erroneous idea has also to a great extent prevailed, owing to the formidable display of figures

and algebraic symbols indulged in by text-books when explaining this simple apparatus and its uses, that both the instrument itself, and the methods of employing it, were complicated and difficult in the extreme. These reasons have militated against the extended use of the Bridge in this country, and up to the present time, its adoption has not been so universal as its merits would seem to warrant.

The first of these reasons at least, no longer exists, since complete sets of bridge apparatus including the galvanometer and all necessary resistances, and having sufficiently wide limits of measurement for any ordinary work, have lately been introduced by J. H. Bunnell & Co., of New York, devised and arranged in a complete form, and fitted up to combine great convenience and efficiency in work, and excellency of finish, with prices which are within the reach of almost everyone; and we may hope that with the rapid increase of knowledge of electrical science, that the latter reason will in turn soon cease to be.

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complete

Description of the Bunnell Galvanometer, Resistance Coils, and Wheatstone Bridge.

The portable bridge apparatus consists of a galvanometer, and a full set of resistances arranged as

a bridge system, together with a neat morocco case, in which both instruments may be placed when not in use, or when being carried from place to place.

The galvanometer is made thus: A delicate magnetic needle is lightly poised in pivots, and carries, at right angles to itself, a light aluminum pointer, extending, on both sides, over a dial having a scale graduated to degrees; the needle is surrounded by three coils of different resistances. The first coil, which is adapted for use in measuring high resistances, or when weak currents are employed, is made of comparatively fine wire, and has a resistance of 70 ohms. The second coil which may be employed with medium resistances and currents, has a resistance of 30 ohms, and the third consists simply of a metal band which passes once or twice round the needle, and its resistance is so small, that it may be ignored.

Each coil may be used separately, or they may be used in series, so as to constitute a continuous coil of 100 ohms, as will be hereafter explained.

The instrument is handsomely mounted in a brass case with glass cover, and is set on a base of vulcanite or hard rubber, which stands on three adjustable leveling screws. It is provided with a damping device, by which the needle is maintained in a stationary position so as to avoid injury when not in use, or while being carried about: and has also a

device by which the movements of the needle are ordinarily limited to variations of a very few degrees; this arrangement, by means of a projecting handle, can be turned round the case so as to be useful, irrespective of the extent of deflection.

Figure 18 is a perspective view, and Figure 19 a plan view of the galvanometer. In the latter, A is

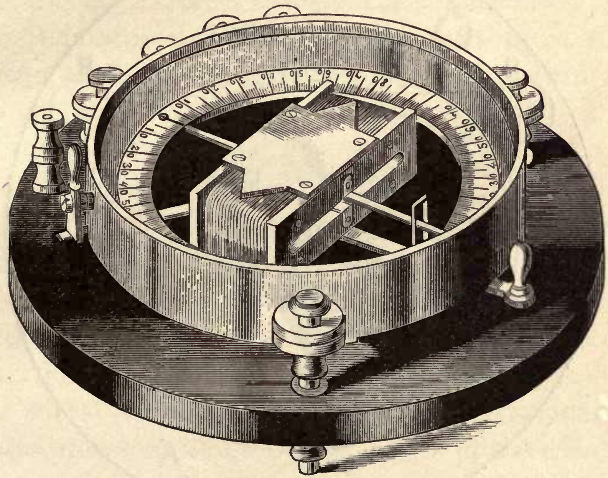

Figure 18.

the rubber base; B, B, B, the leveling screws; 1, 2, 3 and 4 the terminal binding screws, C the coils; N, the needle pointer; L the damping lever, and G the handle of the needle-guide or limiter.

When it is desired to use the entire coil of 100 ohms, that is the 70 and 30-ohm coils coupled in

series, one of the connecting wires must be placed in No. 1 binding screw, and the other in No. 4. When the 30-ohm coil is to be used alone, the wires are placed in 1 and 3.

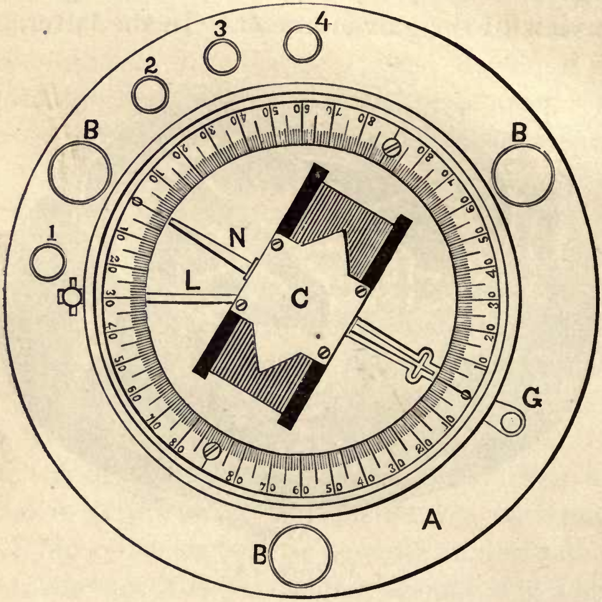

Figure 19.

For very strong currents, and very low resistances we use the band coil, and in that case connect the wires in 1 and 2. The 70-ohm coil may be used alone by connecting the wires with terminals 3 and 4

$C = \frac{E}{R} = \frac{\frac{3}{2}}{12000} = \frac{3}{24000} = \frac{1}{8000}$ amp.

This instrument is sufficiently sensitive for any ordinary measurements, and with one cell of Leclanche battery, gives, through a resistance of 12,000 ohms, using the 100-ohm galvanometer resistance, a deflection of 12 degrees; the 70-ohm coil, under similar conditions, giving a deflection of 7, and the thirty-ohm coil a deflection of 6 degrees.

With no external resistance, a deflection may also be produced with a battery consisting of a steel sewing needle, and a piece of brass immersed in a cup of water.

THE RESISTANCE BOX, OR RHEOSTAT,

Consists of a stout, but handsomely-made box of metal, having a mahogany base, and a hard rubber cover, on which, in addition to the plugs for controlling the resistances, there are six binding screws or terminals, two of which, 1 and 2, are for the battery wires; two others, 3 and 4, for the attachment of the object to be measured, or, as in the case of a line terminating at the distant end in a ground wire; for the line, and home ground wires; while the remaining two, 5 and 6, are usually for the galvanometer wires.

Under certain conditions, which are treated of in a succeeding page, the galvanometer and battery sometimes change places.

Two circuit closing keys are also provided, one of

which, K, controls the battery, and the other, when depressed, completes the galvanometer circuit.

A lever and cam is fitted to the battery key, by which it may be maintained closed, when a constant battery current is required.

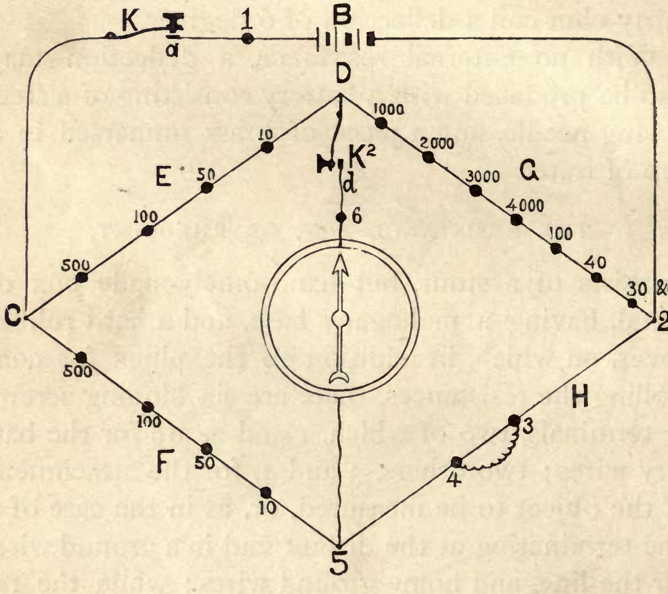

Figure 20.

Figure 20 is a theoretical diagram of the rheostat and galvanometer, when connected up for measurement; and Figure 21 is a diagram of the practical arrangement of the rheostat and keys, showing the connections of the galvanometer and battery.

By comparing the theoretical with the actual arrangements in the figures, it will be at once seen that the electrical connections are identical.

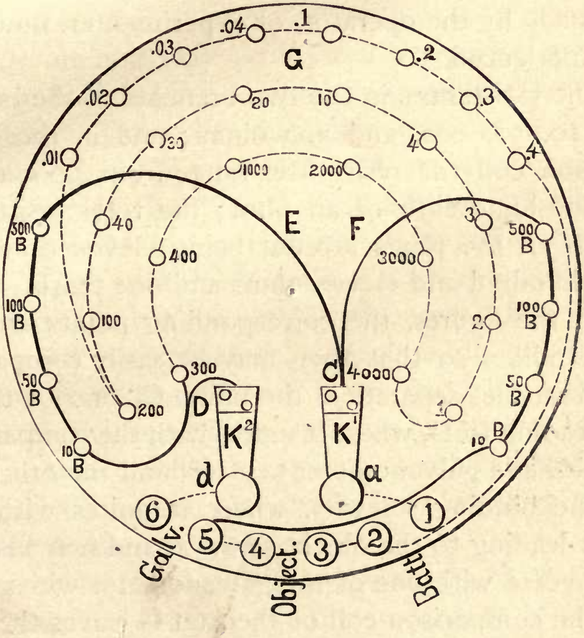

Figure 21.

In the holes opposite the figures are placed brass plugs with rubber handles, which, when withdrawn, introduce resistance in ohms, equal in amount to the figures near them.

Between terminals 1 and 2 the word "Battery" is printed, between 3 and 4 the word "Object," and between 5 and 6 the word "Galvanometer;" the ordinary method of connecting the instruments being thereby indicated, so that no mistake need be made by the operator, or experimenter, however inexperienced.

The resistances in the two branches of the bridge are 10, 50, 100, and 500 ohms; and in the comparison coil the resistances range from 4,000 ohms to one hundredth of an ohm; the total resistance when all the plugs are out being eleven thousand one hundred and eleven ohms and one tenth.

In the figures, the corresponding points are lettered alike, so that they may be easily compared; the branches separate at the point C, one of them, E, leading to D, where it unites with the comparison coils G and galvanometer key K^2; and the other, F, to the binding screw 5, where it unites with the wire leading to the object screw 4, and may also be connected with one of the galvanometer wires.

The comparison coil or rheostat G leaves the first branch at D, and may be traced through the several resistances to terminal 2, where it unites with a wire leading to the object screw 3, and where it is also connected with the return battery wire.

In measuring resistance with this instrument, it will generally suffice to unplug equal amounts of

resistance in the branches E and F; then, when the galvanometer needle is brought to zero, all we have to do is to add the figures of the resistances unplugged in the rheostat which forms the branch G, the total being equal to the unknown resistance required.

This method may be utilized to measure any resistance between 11,100 ohms and one hundredth of an ohm. Therefore it is plain that, even if the branches E and F were unadjustable, the scope of this system is sufficiently wide for the majority of measurements; but as E can be made larger than F, or F larger than E, it follows that the limits of measurement can be greatly enlarged. For if we unplug all the resistance, 660 ohms, in branch E, and but 10 ohms in branch F, we may, theoretically at least, by unplugging but one hundredth of an ohm in the rheostat G, measure as small a resistance as $\frac{1}{6600}$ of an ohm, for as 660 is to 10, so is .01 of an ohm to the answer.

Again, by unplugging 660 ohms in F, 10 ohms in E, and unplugging all the resistances in G, we may measure a resistance as great as $733{,}332\frac{6}{10}$ ohms.

Therefore, by these methods of varying the branch resistances, we are enabled to measure resistances much greater, and much smaller, than those in the rheostat.

MANAGEMENT OF THE GALVANOMETER AND RHEOSTAT.

In using the rheostat or resistance coils, the brass plugs ought to be always clean and bright, as a dirty or oxidized plug does not completely cut its coil out.

When a plug is placed in its socket, it should be slightly twisted so as to produce a good contact; but care must be taken not to twist too hard, or the hard rubber heads may be twisted off, or made loose.

It is always in order, before commencing measurements, to give all the plugs a gentle twist, to see if they are tight; and the brass part of the plugs should be touched as little as possible. In using the rheostat as a bridge, the battery key should always be depressed first, and the galvanometer key afterwards, the latter being depressed only long enough to show the direction of the deflection, until zero is nearly obtained, when it may be firmly pressed.

These precautions tend to prevent injury to the coil and needle of the galvanometer, from sudden and violent currents.

When short pieces of wire or low resistances are being measured, great care must be taken not to apply the battery current too long, as the coils may in that case become heated, and their resistances increased.

One of the first things to be done in using a galvanometer is to find out and note the direction to which the needle deflects under the influence of a given current. If we find that when the zinc pole of a battery is connected with No. 1, the needle deflects to the right, we may know that by reversing the battery, and connecting the copper or carbon pole to that terminal, the deflection will be to the left.

In measurements with the bridge, it is well to connect the battery always the same way; by so doing we are enabled to ascertain, by the direction of deflection, whether we have unplugged too much or too little resistance in the rheostat.

Before laying the galvanometer aside, the needle should be made stationary by the damping lever.

Before commencing to use the galvanometer, it must be carefully leveled by the screws provided for that purpose, and care must be taken that the needle swings freely, and points directly to the zero mark.

As already indicated, the three coils are to enable us to work either with strong or weak currents.

It is a good plan to clean the points of both battery and galvanometer keys occasionally.

PRACTICAL HINTS FOR USE IN WHEATSTONE BRIDGE MEASUREMENT.

As the branch resistances E F are adjustable, the testing operator has the option of choosing any of

them, or, if he pleases, more than one. The question naturally rises, which one, or what is the best proportion? It may be demonstrated, either mathematically or experimentally, that the sensibility or sensitiveness of the instrument is greatest when the resistances in all four branches are alike.

Now, as this identity can only occur when the resistance to be measured is similar, either to any one of the resistances in E and F, or to the sum of any two or more of them, it is obvious that the next best thing is to make the resistances in the branches E F as near to the resistance we are going to measure as we can.

Of course, we do not generally know what the resistance of the object to be measured is, or its measurement would be a superfluous task, but we can often make an approximate estimate of it, and act accordingly.

For instance, if we have a resistance, say, the magnet of an electric bell, and suppose it to be somewhere in the neighborhood of 15 ohms, and we desire to ascertain the actual resistance; we first unplug 10 ohms in each of the branches E and F, because 10 is the branch coil nearest in magnitude to our estimate of 15. Again, if we suppose the unknown resistance to be nearer 50 than it is to 10, we withdraw the 50-ohm plug in E and F; if nearer 100 than 50, we unplug 100 ohms in each branch,

and so on. If, on the contrary, we can form no estimate of the resistance we are about to measure, we can get it approximately by a rough measurement, after which we employ the right arrangement as above, and make a more accurate test.

For example, we wish to measure a line, and have no idea of the magnitude of its resistance: we unplug 500 ohms in the branches E and F, and 500 also in the rheostat; the needle deflects, we will say, to the right; we unplug 200 ohms more and find that the needle deflects still farther to the right, thus showing that we are going in the wrong direction; we then insert the plugs again, leaving only 100 ohms unplugged in the rheostat, and find that the needle now passes the zero point and swings a little to the left, showing that as 500 was too large, 100 is too small. At this point we have ascertained that the unknown resistance is considerably less than 500 ohms, and is greater than 100 ohms. We may now insert the 500-ohm plugs in the branches, and unplug in each branch 100 ohms in place thereof; the needle now swings a little more to the left, because the sensitiveness is increased; we now carefully unplug resistance in the rheostat, trying the galvanometer key after each change, and find that the needle comes to zero when we have withdrawn a total of 175 ohms, which is the resistance required.

For the great majority of measurements, the resistance unplugged in E should be equal to that in F, it being only necessary to make them differ when a resistance is to be measured, either greater than the greatest or less than the least in the rheostat G.

It may be thought by some, that to measure resistances smaller than 10 ohms, it will be best to have no resistance unplugged in E and F.

This is not so; it is absolutely essential that there shall be some resistance in E and F, or there will be no deflection of the needle, the galvanometer in that case being practically short circuited.

It will be always found economical to use as small a battery as possible; moreover, the liability of heating and so altering the resistances of the coils is diminished by so doing; therefore, for all low resistances, one or two cells only should be used, and in most cases, one will be found sufficient.

Large or high resistances, of course, require more, but it is not likely that more than ten cells at the outside will ever be required.

Schwendler gives the following rule for use in Wheatstone Bridge systems: For all resistances under 10,000 ohms, one Daniell cell; above 10,000 and less than 100,000 ohms, ten cells, and for everything above 100,000 ohms, one hundred cells.

As has been already indicated, the Daniell, or crowfoot, gravity battery is the best, on account

of its constancy; but the Leclanche answers very well, if it be more convenient to use it.

Ordinarily the galvanometer is placed between the points D and 5, as indicated in the drawing, and as marked on the Bunnell rheostat.

To obtain the greatest degree of sensitiveness with a given current, the rule is, however, as follows:

"Of the two resistances, that of the battery and that of the galvanometer, connect the greater resistance so as to join the two greatest to the two least of the four other resistances."

To connect in this way, we should generally have to connect the galvanometer with the terminals marked for the battery, and *vice versa*, which is undesirable and would tend to confusion.

Therefore such a method is not here recommended, and, in fact, the usual method of connection will, as a rule, be found to be fully as sensitive as is necessary. When a high resistance is to be measured, and the battery power at hand is not sufficient, it is a good plan to make the change, and see if improved results ensue. Such cases will rarely occur in ordinary practice, and the matter has here been referred to, more for the sake of giving as full information upon the subject as possible, than for any other reason.

INSTRUCTIONS AND FORMULAE FOR MEASUREMENT.

In using the resistance coils which we have described, it must be understood that the branch resistances E F, are those which are denoted by full lines in the diagram, Figure 21, and which stretch along the sides of the resistance box from the binding screws on either side, represented by the numbers 10, 50, 100 and 500 ohms; while the comparison coils or rheostat is marked in dotted lines.

In the succeeding pages, when the branches are referred to, it will be understood that the resistances E F are meant, even when not specifically so stated.

In like manner when the rheostat is spoken of, without a letter of reference, the comparison coil G will be implied.

Supposing now, that we are about to measure resistances, we connect the instruments as follows: Connect the rheostat, battery and galvanometer by wires, as in the diagram Figure 22, with the terminal screws of the rheostat-coil facing the operator. The object to be measured, whatever it may be, must be attached to the two middle binding screws, which are marked as "object" screws, and which we shall hereafter, for brevity, call Nos. 3 and 4;

the galvanometer is connected with the two left-hand screws, which are so marked, and which we may call 5 and 6, and the battery must be connected with the two right-hand screws 1 and 2, which are also marked for it.

We will of course use that coil of the galvanometer which is nearest in resistance to the object we are about to measure. It is not, however, advisable to use the band coil, unless the resistance we are measuring is very small indeed.

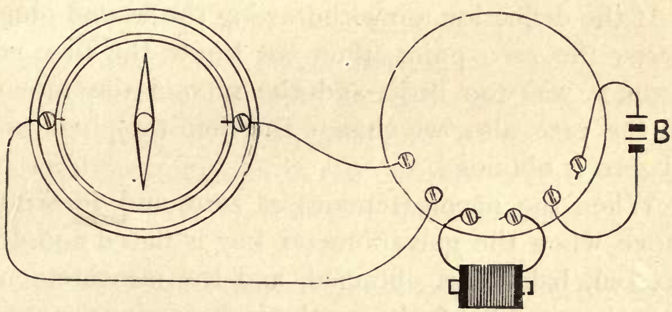

Figure 22.

We now withdraw the proper plugs from each of the branches E F, and unplug resistance in the rheostat G, as near in amount as we can guess, to that we are about to measure.

Pressing the battery key, and immediately thereafter the galvanometer key, we observe which side the needle deflects; we unplug a few ohms more,

and again press the keys; if the deflection increases in the same direction as before, we know at once that we are getting farther away from the true resistance, and that the resistance we first unplugged was too much. If on the contrary, the deflection is lessened, we may know that the first resistance was not sufficient, and we may then fasten the battery key down, and change or remove plugs in the rheostat until the needle comes to zero. In any case where the battery power is not great, the battery key may be fastened down after the first trial.

If the deflection, on withdrawing the second plug, *passes* the zero point, then we know the first resistance was too little, and the second too much. In this case, also, we change the rheostat plugs until zero is obtained.

When the needle remains at zero, and does not move when the galvanometer key is raised and depressed, balance is obtained, and the measurement complete. All of the methods here given, are to be used with the Bridge, except when otherwise stated.

TO MEASURE A RESISTANCE NOT GREATER THAN THE GREATEST, OR LESS THAN THE LEAST IN THE RHEOSTAT.

Let us now assume that we are about to measure the resistance of a local sounder. We see that it is

wound with rather coarse wire, and guess it to be about 6 ohms. We connect the second coil of the galvanometer, and unplug 10 ohms in each of the branches E F, because 10 is the nearest resistance to 6, in those branches; we also unplug 6 ohms in the rheostat G.

Depressing the battery and galvanometer keys, the former first, we find the needle deflects to the right; replacing the 1-ohm plug in the rheostat, and thus leaving but 5 ohms unplugged, we find on depressing the keys that the needle now goes a little to the left. We see at once that the right resistance is not so much as 6, but is more than 5 ohms. We now unplug 0.5, or half an ohm, and the needle comes to zero. All we have now to do is to note the figures unplugged in the rheostat and we have the result 5.5 ohms, which is the resistance of the sounder.

Let the object be a relay, having an estimated resistance of between 100 and 500 ohms. In this case we use the 100-ohm galvanometer coil, and unplug 100 ohms in the branches E F, and 100 also in the rheostat. We fasten down the battery key, and, as before, vary or remove plugs in the rheostat until zero is obtained. We find that the needle comes to zero, when we have unplugged 126 ohms, which is therefore the exact resistance of the relay.

TO MEASURE A RESISTANCE SMALLER THAN THE SMALLEST IN THE RHEOSTAT.

The resistance of a certain length, say three feet, of No. 18 copper wire is required.

Trying to measure with equal resistances in E F, the resistance is found to be smaller than .01 of an ohm, the needle refusing to come to zero.

Unplug 50 in the branch E, and 10 in branch F, and vary the rheostat plugs: the needle becomes stationary, for example, when .07, or seven hundredths of an ohm, are unplugged in the rheostat.

Then 50 : 10 : : .07 : .014 of an ohm, that is, by simple proportion 50 ohms is to 10, as seven hun-hundredths of an ohm is to seven five-hundredths, or fourteen thousandths, of an ohm, which is the resistance of the piece of wire.

TO MEASURE A RESISTANCE LARGER THAN THE LARGEST IN THE RHEOSTAT.

The exact resistance of a conductor, having a resistance which we know to be higher than any in the rheostat, is required. Unplug 10 ohms in the branch E, and 500 in F, and vary the rheostat plugs as in other cases; suppose zero to be obtained when a resistance 4,500 ohms is unplugged.

Then 10 is to 500 as 4,500 is to the required resistance, *i. e.*, 225,000 ohms.

Of course the figures in all of the above are given merely for the sake of illustration. Much greater extremes, both higher and lower, may be measured with equal facility by increasing the inequality between the branches E and F.

To measure a telegraph line in metallic or loop circuit, the two ends of the circuit are connected to the resistance box terminals 3 and 4, just as with any other conductor; and the procedure is then according to the examples given above.

TO MEASURE AN ENTIRELY UNKNOWN RESISTANCE.

It has been stated that the best results are to be obtained with the bridge, when the resistances unplugged in the branches E and F, are those nearest to that which is to be measured; because the nearer the four sides of the parallelogram are to one another in resistance, the more sensitive is the galvanometer.

If we have no idea of the magnitude of the resistance we are going to measure, it is clear that we cannot do this. In such a case Kempe recommends the following method: "Take out, say the 100-ohm plugs in E and F, and then, having adjusted the resistance in the rheostat G, so as almost to obtain equilibrium, change the 100-ohm plugs in E F for the 50 or 500-ohm plugs, and see if the deflection is increased. As soon as the plugs which produce the

greatest deflection are found, we can then finally vary the plugs in the rheostat until exact equilibrium is attained. Furthermore the same device may be adopted when measuring with unequal resistances in E and F."

TO MEASURE THE RESISTANCE OF A LOOP OR METALLIC CIRCUIT.

Connect the two ends of the circuit to the resistance box binding screws 3 and 4, and proceed as before.

TO MEASURE A RESISTANCE BY SUBSTITUTION, USING ANY GALVANOMETER, AND HAVING BOTH TERMINALS OF THE RESISTANCE AT HAND.

Connect the galvanometer in direct circuit with a sufficient battery to give a deflection of any number of degrees not over 40 or under 15, and with the object to be measured, and note the deflection obtained.

Remove the object and replace it by a rheostat; unplug resistance in the rheostat, until the same deflection is again obtained, when the resistance unplugged will be equal to that of the unknown resistance measured; that is, of course, subject to any change which may have taken place in the condition of the battery *ad interim.*

The galvanometer supplied with the Wheatstone Bridge set is not suited for this class of measurement, as the movement of its needle is limited; it being intended solely for methods of measurement in which the absence of a deflection, or zero, denotes that balance is obtained between a known and unknown resistance. It is also too sensitive for small resistances.

Any tangent or sine galvanometer will do, or even a good compass galvanometer, if no other can be obtained; and in all cases, as in the bridge system, that coil of the galvanometer (if it has more than one) should be used, which approximates the most nearly to the resistance to be measured.

To diminish the time consumed in substituting the unknown for the known resistance as much as possible, a button switch may be used, as shown in the diagram, Figure 23.

The rheostat provided for the bridge set may be used, if the resistance to be measured is not greater than the total resistance, which may be unplugged in its resistance coils; and if it is used, the connections must be as follows: Connect one pole of the battery to rheostat post No. 1, and the other to one of the galvanometer terminals; connect the opposite galvanometer terminal to the switch-button, as shown in the figure.

Attach the two wires of the unknown resistance to binding screws 5 and 6 of the rheostat, and one

of the switch-studs also to No. 6. Finally, unite post 2 of the rheostat with the other stud of the switch.

In measuring, first turn the switch to the side that connects with the object to be measured. Observe the deflection, call it, say, 30 degrees; turn switch to the rheostat side, and unplug resistance until the needle again shows 30 degrees. Turn the switch rather quickly once or twice to see if the same deflection is maintained on either side, and when no change is observed, add up the resistance unplugged, which will be the resistance required.

TO MEASURE BY SUBSTITUTION A RESISTANCE OF WHICH ONE END ONLY IS AT HAND, THE OTHER BEING CONNECTED WITH THE EARTH AT A DISTANT POINT.

Suppose the unknown resistance to be a telegraph line, and our apparatus to be a tangent galvanometer, a rheostat and a battery: connect one pole of the battery to earth, and the other with one of the galvanometer terminals; unite the other galvanometer terminal to the line wire, and observe the deflection.

Now disconnect the line from the galvanometer, and the ground wire from the battery, and insert the rheostat in their place, connecting one of the rheostat posts with the battery, and the other with

the galvanometer; unplug resistance in the rheostat till the galvanometer needle shows the same deflection as when the line was in circuit.

The unplugged resistance denotes the resistance of the line.

The button-switch may be here also taken advantage of to save time, and when it is used, it

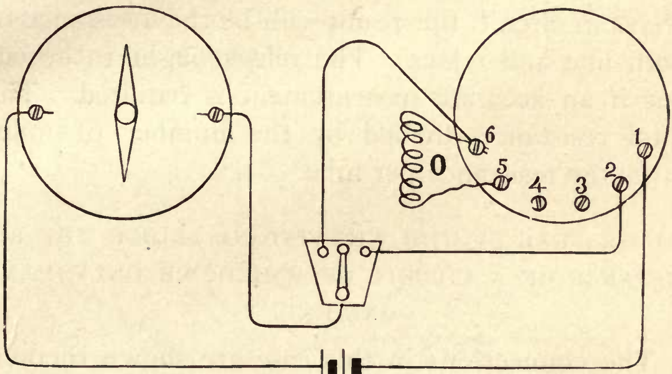

Figure 23.

must be so connected that turned one way the battery and galvanometer are connected with the line, and when turned the other way with the rheostat. If we have no other rheostat than the one belonging to the bridge set, this may be used by uniting one battery pole with post 1 of the rheostat; the other battery pole with one of the galvanometer terminals; post 2 of the rheostat to one side of the

button-switch; post 5 of the rheostat to a ground wire, and post 6 of the rheostat to the line to be measured, and also to the other side of the button-switch. The button or movable bar of the switch is then attached to the remaining galvanometer post.

The course of the circuits may readily be traced out by reference to Figure 23.

If the line to be measured is long, and has several relays in circuit, the result will be the resistance of both line and relays. The relays ought to be cut out if an accurate measurement is required. The total resistance divided by the number of miles gives the resistance per mile.

TO MEASURE BY THE WHEATSTONE BRIDGE THE RESISTANCE OF A CIRCUIT OF WHICH WE ONLY HAVE ONE END.

The connections in this case are shown theoretically in the diagram Figure 24, and are practically made by uniting the line wire to be measured to screw 4, and a ground wire to screw 3 of the rheostat. Connect the battery poles with rheostat screws 1 and 2, and the galvanometer with 5 and 6, as indicated by the words stamped between the binding screws.

Now proceed according to general instructions. Suppose the line to be measured to be 30 miles long, and that we know it to be built of No. 12 iron wire. We also know that No. 12 galvanized iron

wire has a resistance per mile of about 32 ohms; this, multiplied by 30 for the number of miles, gives an estimated resistance of 960 ohms. We therefore unplug from the branches A and C, a reasonably high resistance, for example, 500 ohms in each.

We then vary the plugs in the rheostat B, until the needle remains at zero. Supposing this occurs when 980 ohms are unplugged, 980 ohms is the total resistance of the line, being a little over the estimated resistance.

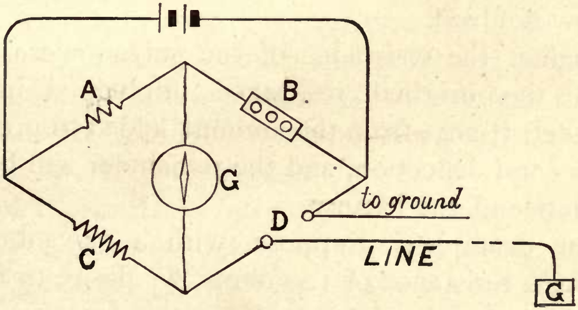

Figure 24.

TO MEASURE THE INTERNAL RESISTANCE OF A BATTERY.

There are several methods of determining the internal resistance of a battery; we give a few of the easiest and best.

1st—*By a sine or tangent galvanometer.* Connect the galvanometer, the battery to be measured,

and a rheostat in circuit together, and observe the deflection; all the plugs being left in the rheostat, the only resistance in circuit, is practically that of the galvanometer and of the battery itself. If the deflection is too great, unplug any convenient resistance; once more observe the deflection produced, and find its tangent. Halve the tangent, and by reference to the table find what deflection the halved tangent corresponds to.

Now unplug resistance in the rheostat, till the latter deflection is produced. The total resistance is now doubled.

Deduct the resistance of the galvanometer, and twice the original resistance unplugged in the rheostat, if any, from the amount added to produce the second deflection, and the remainder will be the resistance of the battery.

For example: Suppose, with a galvanometer having a resistance of 100 ohms, we desire to measure the internal resistance of a certain battery; after joining the battery, galvanometer, and rheostat as described, we find the deflection to be 50 degrees; we consider this to be too high for an accurate measurement, and to reduce it, we unplug 60 ohms. This brings the deflection down to 40 degrees.

Referring to the table of tangents, we find the tangent of 40 degrees to be .839, the half of which is .4195. The number of degrees which corresponds

most nearly to the latter tangent, is 23; we therefore unplug enough resistance to bring the deflection down to 23 degrees, let us say 300 ohms.

Now as the total resistance is doubled, it follows that the current is halved. To ascertain the resistance of the battery, we double the resistance first unplugged, viz.: 60 ohms, and add the sum, 120 ohms, to the resistance of the galvanometer, 100 ohms; then deducting the total 220 ohms from the resistance added 300 ohms, we find the remainder to be 80 ohms, which is the internal resistance of the battery. Of course, if we do not find it necessary in the first place to reduce the deflection by adding resistance, it is only necessary to subtract the resistance of the galvanometer from the amount added to halve the tangent.

2nd Plan. If we have two cells exactly alike, we may join them in opposition to one another, so that they generate no current of their own, and then measure them, either with a tangent, sine, or differential galvanometer, or by a Wheatstone Bridge, just as we would measure any other resistance. The resistance of one cell will be half that of the two.

3rd Plan. This method is shown theoretically by the diagram, Figure 25, and the practical arrangement in connection with the bridge rheostat will be hereafter described. The resistance coils R, are joined up in direct circuit with the galvanometer G,

and the battery B, which is to be measured, and a shunt S, is placed so as to connect the poles of the battery by a second circuit, parallel to that in which the galvanometer and rheostat are included.

The shunt should have a resistance exactly equal to the other external resistances, *i. e.*, the galvanometer and whatever resistance is unplugged in the rheostat, and these again should be proportionate

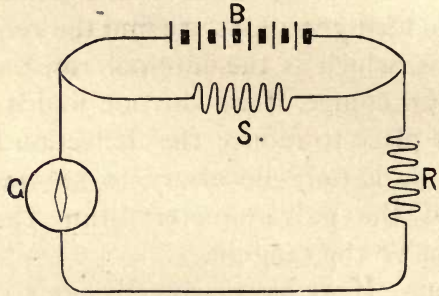

Figure 25.

to the supposed resistance of the battery to be measured. When connected as shown, the shunt, and the galvanometer and rheostat, present a joint external resistance to the battery, and the current from the battery B, divides itself through the two equal resistances, half of it passing through the shunt S, and the other half through the galvanometer G and rheostat R.

Observe the deflection of the needle at G. Now remove the shunt; the whole current must then

pass through G and R, and the deflection at G accordingly increases. The external resistance between the poles of the battery is now double what it was when the shunt was connected, because, by the laws of parellel or derived circuits, the resistance of two equal circuits together, is just half that of either of them alone; but the internal resistance of B remains unchanged.

Now unplug resistance in R, till the same deflection is produced as at first, and the extra resistance unplugged will be exactly equal to the internal resistance of the battery B.

For example: A galvanometer whose resistance is 100 ohms, and a battery, the resistance of which is to be ascertained, are connected in circuit with a resistance of 400 ohms in the rheostat; a shunt of 500 ohms is now caused to connect the battery wires, and we observe the deflection to be 24 degrees. Removing the shunt, the whole current passes through the galvanometer, and the deflection increases. To bring it back to 24 degrees, let us assume that we have to unplug 60 ohms, which is therefore the resistance of the battery.

To use the Bunnell Bridge rheostat, the connections must be made in the following manner:

The poles of the battery to the rheostat terminals 1 and 6; the galvanometer to 3 and 6; also by a short wire 5 and 6 are to be joined. To remove

the shunt, take out the short wire connecting 5 and 6.

4th. The fourth plan, and in some respects the best, will now be described. It is often, from its discoverer, called Mance's method, and it consists in placing the battery whose internal resistance is to be measured, in the fourth branch of a Wheatstone Bridge, and varying the resistance of the other branches.

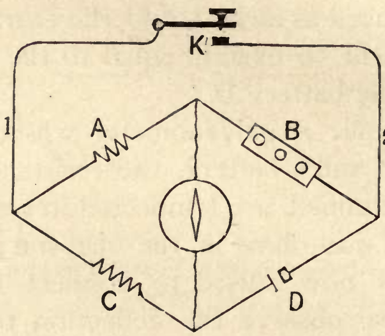

Figure 26.

Referring to Figure 26, which clearly shows the arrangement, B is the rheostat, A and C the other branches, and the battery is inserted at D. The galvanometer is kept in its usual place on the cross wire, and a key K is put in the usual place of the battery, by which we can close or open the circuit of the wire 1, 2, whenever we please.

The battery when connected as shown in the figure, in the branch D, produces a certain deflection of the needle; the resistance in the other branches, chiefly that in the rheostat B, are now varied and adjusted, not until the needle comes to zero, as described in previous measurements, but until the deflection of the needle is the same, whether the key is pressed or not.

When this condition is reached, the battery resistance is balanced by the other branches. If the resistance unplugged in A is equal to that in C, the amount unplugged in B, will equal the required internal resistance of the battery in D. If A and C are unequal, the required resistance will as usual be found by proportion, A being to C as B is to D.

In this method of measuring the resistance of the battery, the galvanometer resistance need not be considered. Another advantage is, that the electromotive force of the battery need only be steady during the short periods of time occupied in depressing and raising the key.

To make the proper connections, we connect the battery with the object posts 3 and 4; unite posts 1 and 2 together by a short wire, and connect the galvanometer as usual with posts 5 and 6.

In measuring, first press the galvanometer key, and then the other. This method as described in most of the textbooks, and works on electrical

measurement, is apparently very easy and simple. Some care, however, is necessary in order to perform it successfully, for, with a galvanometer of any sensitiveness at all, the deflection will be so great as to be unreliable, and sometimes the needle will even deflect to its utmost limits.

This is a point on which most of the textbooks are dumb, yet it is a most important one. Some means must evidently be adopted to bring the deflection within reasonable limits, and several plans have been proposed. This may sometimes be done by making the branch resistances unequal, balancing, for example, 100 in A, against 10 in C, or even a still greater inequality. If this is not effectual, the desired end may be gained by giving the needle an initial bias to one side by means of a permanent bar magnet, or, what is equivalent to this, bringing the needle nearly back to zero by approaching the permanent magnet to it.

Or, we may shunt the galvanometer by connecting its terminals by a cross wire of suitable resistance; an adjustable resistance being best, of course; if such a one is not easily attainable, almost any may be made to answer; a Morse sounder, for example, may be looped to the galvanometer posts, after the other connections are completed.

Supposing then, that the galvanometer has a resistance of 100 ohms, and the sounder 5 ohms, 100

parts of the entire current will pass through the sounder coils, and 5 parts through the galvanometer. A smaller and more convenient deflection is thus produced.

Or again, we may insert resistance in the galvanometer circuit between it and the rheostat (that is, at any point in the bridge wire), until the deflection is brought low enough.

All of the above plans are easy of application, and the most convenient may be adopted. The writer has very successfully employed the permanent magnet.

TO ASCERTAIN THE RESISTANCE OF A GALVANOMETER.

There are several methods of measuring the resistance of a galvanometer.

If we have a second galvanometer, the easiest and most obvious way of ascertaining the resistance of either, is, of course, to regard them as any other ordinary resistance to be measured, using one of them as an instrument with which to measure the other, in connection with the bridge, as already described.

But we often find it desirable to know the resistance of the galvanometer which we are using, when we have no other to use as a measuring instrument.

We will describe the two simplest methods of finding the galvanometer resistance under such circumstances.

First. Using the Wheatstone Bridge. This plan is the counterpart of the bridge method of measuring the internal resistance of a battery, and was derived by Sir William Thomson from that method.

Figure 27 is a diagram of the arrangement, A and C being as usual the branch resistances, and B the comparison rheostat; the galvanometer is placed in branch D, instead of being in the cross wire; in

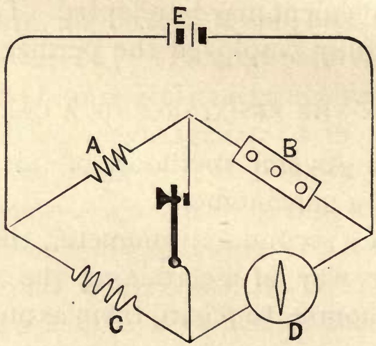

Figure 27.

the regular place of the galvanometer is a circuit-closing key, so that we may easily and quickly connect and disconnect the two points which would ordinarily be connected with the galvanometer.

The battery E is in its usual position, and, of course, the current flowing from it passes through the branches of the bridge, causing the galvanometer needle to deflect.

The resistances in the other branches, principally the branch B, are then adjusted until the deflection remains unaltered, whether the key in the cross wire be depressed or not. When this occurs, a balance is evidently made, and consequently we get the resistance of the galvanometer by the usual proportion; thus, as A is to C, so B is to the resistance of the galvanometer in D.

If, for example, we have 100 ohms unplugged in A and C, and to effect a balance, we have to unplug 250 ohms, the first two branches being equal, the galvanometer in D is also equal to the amount unplugged in B, that is, 250 ohms.

It will be observed, that though this is not a null method, in the strict sense of there being no current in the galvanometer, and no deflection of the needle, it is so in view of the fact that the deflection when balance is established, does not change when a certain contact is made. To clearly understand this method, we must refer again to the principle of the bridge. From what has already been explained of the operation of the bridge, it is easy to see that when we are measuring an ordinary resistance in the usual way, before the balance is made, a current is flowing through the galvanometer, or its needle would not be deflected; consequently, if we make any change in its resistance, the strength of current flowing in all the branches will be affected.

If, on the contrary, balance is established, the needle stands at zero, therefore no current is passing through the galvanometer, and it follows, that if no current is passing through the galvanometer, that we may open the cross wire, or even take away the galvanometer, or make any other change in the cross wire resistance, without affecting the currents in the branch wires at all, and upon these principles the above method of measuring the resistance of a galvanometer depends.

We connect the instruments in the following manner:

Battery as usual to the rheostat terminals 1 and 2. Galvanometer to the object terminals 3 and 4. Connect also the ordinary galvanometer terminals 5 and 6 by a short wire.

In measuring, we first depress the battery key, then galvanometer key, and then vary the plugs until the deflection does not change when the latter is pressed. When we get a deflection that only varies a little when we press the galvanometer key, we may fasten the battery key down, and manipulate the galvanometer key only, until a constant deflection is reached. The same caution is necessary in using this method, as in the Mance method of measuring the resistance of a battery, and for the same reason; viz.: the extreme deflection of the needle which ordinarily will take place.

To avoid this, the first thing to be done, is to reduce the sensitiveness of the galvanometer by unplugging unequal proportions in the bridge, and making the galvanometer side of much the highest resistance, so that the major part of the current will pass through the rheostat. We may, for example, unplug 10 ohms in A, and 500 in C, and then vary the resistances in B.

We may also reduce the battery power to a single cell. If the current is still too strong for accurate measurements, we must adopt one of the following expedients:

Either shunt the galvanometer by a resistance which is known, and measure the joint resistance of the shunt and galvanometer in parallel circuit; and afterwards calculate the resistance of the galvanometer, from the difference between the resistance of the parallel circuit, and the known resistance of the shunt.

Or shunt the battery by a resistance sufficient to reduce the deflection to reasonable limits.

Or weaken the current by inserting sufficient resistance in the battery circuit.

Or insert a sufficient resistance in the galvanometer circuit, measure both, and then measure the added resistance alone, and subtract the lesser from the greater resistance; the remainder will be the resistance of the galvanometer.

Or, as in measuring a battery resistance, after obtaining a high deflection, bring the needle back almost to zero, by placing a permanent magnet near it.

To shunt the galvanometer, however, if we have a shunt convenient, is the preferable and most elegant way; and when this mode is adopted, we first measure the resistance which is to serve as the shunt, and then loop it by wires to the galvanometer terminals.

Let us suppose the shunt measures 100 ohms; and that when in parallel circuit with the galvanometer, as shown in Figure 28, the deflection is reduced to a reasonable figure, say 30 degrees. We

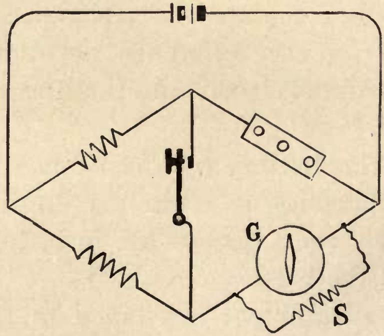

Figure 28.

find the joint resistance of shunt S, and galvanometer G, to be 75 ohms.

Now the resistance of the shunt being 100 ohms, and the joint resistance of both shunt and galvanometer 75 ohms, how shall we, from these figures, ascertain the galvanometer resistance?

This is so much easier to explain by the aid of algebra, that it is not surprising that the text-book writers, always drop into that branch of mathematics, just as Silas Wegg used to drop into poetry; we will, however, attempt to make the thing plain, using no other mathematics than arithmetic.

Resistance is the converse of conductivity; therefore, if the resistance of two wires or circuits are known, their conducting power is found by dividing unity by their resistance; and we say that the conductivity of any wire is the reciprocal of its resistance. The reciprocal of any number is the fraction obtained by dividing one by that number; and that of any fraction is the fraction itself inverted. Thus, the reciprocal of 4 is $\frac{1}{4}$ or .25, and, conversely, the reciprocal of .25, or $\frac{1}{4}$, is $\frac{4}{1}$, which, of course, is equivalent to 4.

We are now prepared to apply these principles to the case we have in hand, and, in fact, to any similar case.

The resistance of the shunt being 100 ohms, its conducting power is the reciprocal of 100, *i. e.*, $\frac{1}{100}$.

The joint resistance of the galvanometer and shunt being 75 ohms, its conducting power is the

reciprocal of 75, *i. e.*, $\frac{1}{75}$. Let us call the combined circuit G S; the shunt S, and the galvanometer G.

It follows now, that the conductivity of G S being $\frac{1}{75}$, and that of S alone $\frac{1}{100}$, that of G alone must be the difference between them, and so it proves, for subtracting $\frac{1}{100}$ from $\frac{1}{75}$, the remainder is $\frac{25}{7500}$; which by cancelling becomes $\frac{1}{300}$; this latter fraction representing the conducting power of G alone.

We have stated that the reciprocal of a fraction is the fraction itself inverted; and inverting $\frac{1}{300}$, it becomes $\frac{300}{1}$, or 300, which is the required resistance of the galvanometer G.

Second. The second plan of finding the resistance of the galvanometer may be adopted as an alternative method, and is as follows:

Place the galvanometer in circuit with a rheostat or resistance box, and a battery of very low internal resistance; unplug any resistance, say 400 ohms, and note the deflection: we will suppose it to be 20 degrees.

Then put the plugs back, withdrawing resistance from the circuit, until the former deflection is doubled, so as to reach 40 degrees; there is now, we may assume, 300 ohms unplugged. We then multiply the two resistances by their respective deflections, subtract the smaller product from the

larger, and divide the result by the difference between the two deflections.

To make the connections properly with the bridge rheostat, we connect the two poles of the battery with the rheostat terminals 1 and 6, and connect the galvanometer with terminals 2 and 6. Leave terminals 3, 4 and 5 unattached.

With the figures we have used, we first multiply the 400 ohms by its own deflection 20, giving a product of 8,000. Then multiplying 300 by its own deflection 40, equals 12,000. 12,000 minus 8,000 leaves 4,000; and that amount divided by 20, which is the difference between the deflections 20 and 40 degrees, gives us as the resistance of the galvanometer 200 ohms.

TO MEASURE THE RESISTANCE OF THREE WIRES WITHOUT USING A GROUND WIRE.

If we have three line wires running between the same terminal stations, we can measure the resistance of all of them without an earth wire, and the measurements will be more correct than if they were measured as a grounded circuit, because errors which arise from defective ground wires, and also those likely to accrue from earth currents, are thus avoided.

We may number the wires 1, 2 and 3, and we desire to know the resistance of each.

Have the distant ends of No. 1 and No. 2 connected, and measure the loop. Let us assume the resistance of this loop to be 4,000 ohms. Then make a second loop by connecting 1 and 3, at the distant end; which, when measured, is found to have a resistance of 5,000 ohms.

Lastly, let us loop Nos. 2 and 3, and measuring again we find the resistance to be 8,000 ohms. Now from these results we have to get the required resistance of the three several lines.

To get the resistance of No. 1, we add the first two results together, that is, the 4,000 and the 5,000 ohms; the sum is of course 9,000, which is clearly the sum of the resistance of all the wires, the first being doubled, as it was measured both times.

We now subtract the third result from the sum obtained, deducting 8,000, the resistance of the loop, composed of Nos. 2 and 3, from 9,000, and we find the remainder to be 1,000: this, divided by 2, because No. 1 was twice measured, gives us 500 ohms as the resistance of No. 1.

The resistance of No. 2 is similarly obtained; that is, by adding the first and third result, subtracting the second, and dividing by two; and is found to be 3,500 ohms. The resistance of No. 3 is likewise found by adding the second and third results, subtracting the first from the sum and dividing by 2; leaving the final result 4,500 ohms.

The calculation can be expressed in figures as follows:

$$\text{Resistance of No. 1} = \frac{4000+5000-8000}{2} = 500$$

$$\text{Resistance of No. 2} = \frac{4000+8000-500}{2} = 3500$$

$$\text{Resistance of No. 3} = \frac{5000+8000-4000}{2} = 4500$$

We can of course easily prove that these final results are correct, by adding them together.

TO MEASURE THE INSULATION RESISTANCE OF A LINE-WIRE.

First. With the Bridge. Use the fine wire coil of the galvanometer. Make the connections precisely the same as if the wire resistance were to be measured; that is, connect the battery, (which should for insulation measurements be not less than 10 cells), to rheostat terminals 1 and 2; ground wire to 3; line to 4; and galvanometer to 5 and 6. Measure first with equal resistance in the branches. If the insulation resistance is not greater than the total amount contained in the rheostat, zero can be obtained.

If we find that the needle will not come to zero, we now unplug unequal resistances in the branches, that of F being the greater.

Let us, for example, unplug 100 ohms in E, and 500 in F, and vary the plugs in the rheostat, until the needle comes to zero. Then, by the usual proportion, the resistance 100 in E will bear the same ratio to the 500, unplugged in F, as the amount unplugged in the rheostat G does to the insulation resistance measured.

Suppose the line is 20 miles long, and to bring the needle to zero, we have to unplug in the rheostat 3,000 ohms; then as 100 is to 500, so 3,000 is to 15,000, which is the required insulation resistance; and which, multiplying by 20, for the number of miles, gives a mileage insulation of 300,000 ohms.

Second. With a tangent galvanometer. Find first the constant of the galvanometer: that is, ascertain what deflection the galvanometer gives with a standard battery, through a standard resistance. Refer to the table for the tangent of the constant. Then connect the galvanometer in circuit with the line whose insulation resistance is to be measured, and with the same battery that was used to take the constant.

One pole of the battery must be connected to earth and the other to galvanometer terminals.

The other galvanometer terminal must be attached to the line, and the distant end of the line left open. Note the deflection. Find its tangent, by reference to the table. Then the tangent of the latter deflec-

tion is to the tangent of the former as the standard resistance is to the insulation resistance required.

For example: With a tangent galvanometer, connected in circuit with ten cells of battery and a standard resistance of 5,000 ohms, we get a deflection of 40 degrees. This we call the constant. Referring to the table of tangents, we find the tangent of that deflection to be .839.

Then connect the same galvanometer and battery to the line; the resulting deflection being, let us say, 10 degrees; the tangent of which is .176. Now, as tangent .176 is to tangent .839, so is 5,000 ohms to the required insulation resistance, 23.835 ohms.

$$\frac{.839 \times 5000}{.176} = 23{,}835.$$

To find the insulation resistance per mile, multiply the result of the measurement by the number of miles. Thus: if the line is 50 miles long, and the insulation resistance as above, we multiply 23,835 by 50, and the product, 1,191,750 ohms, is the insulution resistance per mile; which is a very fair grade of insulation.

Insulation should never be allowed to fall below 20,0000 ohms per mile, in wet weather.

The line whose insulation is to be measured, must always be open at the distant end.

TO MEASURE, BY MEANS OF THE BRIDGE, THE RESISTANCE OF A LINE WITH THE BATTERY AT THE DISTANT END.

In this case, it is supposed that there is no suitable battery at the testing station, and that at the distant station there is one. The formula is identical in principle with Mance's method of measuring the internal resistance of a battery; and the arrangement of the apparatus is also similar.

Figure 29 illustrates this method of testing.

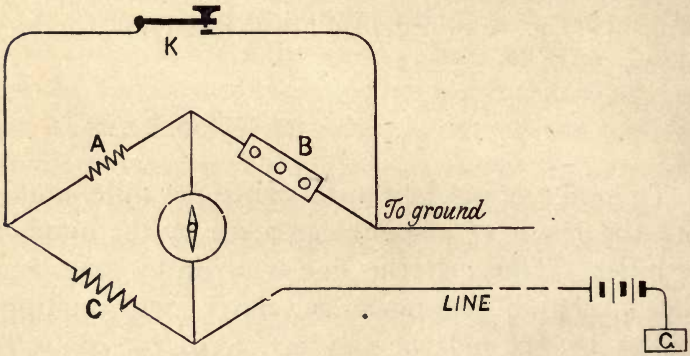

Figure 29.

The key only is left in the ordinary place for the battery. A ground wire is attached to the rheostat branch B, and the line to the branch D.

In measuring, if the resistance of the line is not greater than the total resistance in the rheostat,

equal resistances may be unplugged in the branches A and C. If it *is* greater, it will be necessary to make C greater than A. The plugs in the rheostat branch B are now to be varied until the deflection of the needle remains the same, whether the key K be pressed or not.

When this occurs, the line is balanced, and by the usual process we calculate the unknown resistance, which will be that of the line, plus the internal resistance of the battery. This ordinarily can be calculated and deducted from the total measured resistance. The remainder is the resistance of the line alone.

The entire operation is simply that of measuring the internal resistance of a battery with very long terminal wires. In practice, we connect the rheostat terminal screws as follows: Unite posts 1 and 2 together by a wire. Attach a ground wire to post 3; the line to post 4, and the galvanometer to 5 and 6.

Suppose the line to be measured to have a length of 300 miles, and to consist of No. 9 galvanized iron wire. To decide what the branch resistances should be, we may first roughly calculate the resistance of the line. Calling the resistance per mile of No. 9 galvanized iron wire 16 ohms, the resistance of the whole line will be 4,800 ohms.

Since this does not exceed the total resistance

which may be unplugged in the rheostat, we may use equal resistances in the branches.

We unplug 500 ohms in A and in C, and change the plugs in the rheostat, finding, perhaps, that the deflection remains constant when we have unplugged 5,100 ohms.

Then 5,100 ohms is the resistance of the line and battery. We find that the battery consists of eighty Callaud cells, and assuming one Callaud cell to have a resistance of 2 ohms, which gives a total of 160 ohms for the whole battery, we deduct that amount (160) from the 5,100, which leaves us, as the resistance of the line, 4,940 ohms.

As in measuring the internal resistance of a battery by the Mance method, we shall probably have to reduce the deflection by one of the plans described in the explanation of that method, or by reducing the battery at the distant station.

TO MEASURE A LINE WITHOUT A BATTERY.

Occasionally, earth currents are so strong on a line, as to make it impossible to make an accurate measurement. In this case, if the earth current is of constant direction, the best way to proceed is to disconnect the battery altogether, and then, regarding the earth current as the battery power, proceed as in the plan just described of measuring the line, using a distant battery.

TO COMPARE, MEASURE, OR ESTIMATE THE ELECTRO-MOTIVE FORCE OF A BATTERY.

There is no absolute permanent standard of electro-motive force, because no battery can stay in an absolutely constant condition, and therefore we cannot arbitrarily determine the force of any particular battery in standard units (volts), but can only compare a battery whose electro-motive force is not known, with one whose force we know. This comparison may be made in several ways.

We will describe one or two of the easiest and plainest methods in use.

First: Join up a number of the cells whose electro-motive force we desire to know, in circuit with a galvanometer, and also with a number of cells whose electro-motive force we do know—the latter being connected in opposition to the former, —then adjust the number of cells of each series, so that one series just balances the other, and no current passes. When this point is reached, the needle has no deflection, and the relative force of the batteries may thus be determined. For example: We desire to know the electro-motive force of a bichromate battery of 10 cells, and we have a Daniell battery with which we can compare it. We know that a Daniell cell in good order is about one volt; in exact terms, 1.079 volts. We connect

one pole—the zinc, for instance—of our bichromate battery, to one terminal of the galvanometer, and the carbon pole to the copper pole of a battery composed of an equal number of Daniell cells; the zinc pole of the Daniell battery is connected to the other terminal of the galvanometer. We see that the needle deflects. One of the batteries is evidently stronger than the other. We add another cell of the bichromate battery, and the deflection increases; this shows that we are on the wrong tack, and we reduce the bichromate battery to its original number, and add cells to the Daniell instead, until the needle deflects no longer. Suppose we have to add 6 cells to bring the needle to zero. It thus takes 16 Daniell cells to balance 10 bichromate cells, showing that the E. M. F. of the bichromate battery is to that of the Daniell as 16 is to 10, or cancelling, as 8 is to 5.

To find the value in volts, multiply the E. M. F. of one Daniell cell 1.079, by the number of cells 16, and divide by the number of bichromate cells 10. The quotient is 1.726, which is the value of bichromate cell.

This plan can be adopted with the galvanometer of the bridge set.

Second: With a tangent galvanometer. The electro-motive forces of two batteries are to be compared. Call them A and B. Connect up A in

circuit with a galvanometer and rheostat. Unplug sufficient resistance to produce a convenient deflection. Observe the tangent of the deflection, and note also the total resistance in circuit: that is, the sum of the resistances of the battery galvanometer, and whatever is unplugged in the rheostat.

Now remove battery A, and substitute battery B. If the internal resistance of B is different from A, the resistance unplugged must be changed, and re-adjusted, until the total resistance in circuit is the same as before. Again note the tangent of the deflection.

The electro-motive force of A is now to the electro-motive force of B, as the first tangent observed is to the second.

For example: We have two batteries, each of which is composed of 20 cells. We call the first battery A, and its electro-motive force is 20 volts. We wish to determine the E. M. F. of the second battery which we may call B.

Suppose A to have a resistance of 60 ohms, and the galvanometer 100 ohms. We unplug 800 ohms in the rheostat, making a total resistance of 960 ohms. With this resistance we find that the needle deflects to 35 degrees. Referring to the table of tangents, we find that the tangent of 35 is .70.

We note the above facts, and then disconnect battery A, putting battery B, which has a resistance

of 100 ohms, in its place. We must now reduce the resistance unplugged in the rheostat, to 760 ohms, so as to make the total resistance the same as before, *i. e.*, 960 ohms.

With this resistance suppose we now get a deflection of 42 degrees, the tangent of which is .90; then as .70 is to .90, so is the E. M. F. of A, to the E. M. F. of B; and since the E. M. F. of A was 20 volts, the calculation is that .70 is to .90, as 20 volts is to $25\frac{5}{7}$ volts.

A third method consists in placing each battery alternately in circuit, varying resistance to produce the same deflection with each, then adding the required resistance in both cases, to produce lower, but again similar deflections; the electro-motive forces then being directly proportional to the added resistances, which in both cases were required.

To illustrate: No 1 battery, which we will suppose has a known E. M. F. of 25 volts, is placed in circuit with a galvanometer and rheostat. Unplug say 2,000 ohms, and note the deflection, which is 30 degrees. Adding 200 ohms to that already unplugged, brings the deflection down to 24 degrees Disconnect No. 1 and connect No. 2 in its place. We find that to produce the same deflection as the one we had first—30 degrees, we have to unplug but 1,800 ohms; and by adding 150 ohms, we bring the

deflection down to that produced by adding when No. 1 was in the circuit, 24 degrees.

Now the amount added in the measurement of No. 1, that is 200 ohms, is to the amount added in the measurement of No. 2, viz., 150 ohms, as the E. M. F. of No. 1, that is 25 volts, is to 18¾ volts, the E. M. F. of No. 2.

It is a good idea to keep a record of the deflection which, with a given battery, having a known E. M. F., and given resistance, will be produced upon a given galvanometer, because, by so doing, we can always with the same galvanometer use that deflection as a standard.

TO LOCATE A BAD JOINT, OR OTHER DEFECTIVE POINT, PRODUCING A HIGH RESISTANCE IN A LINE CIRCUIT.

A line circuit, whose resistance, when in good order, should be (as known from prior measurements, or by calculation), for example, about 3,000 ohms, is found to require a much larger battery power than it ought, to produce a current of required strength, and on being tested, shows a resistance of say 10,000 ohms: the cause is probably a bad or unsoldered joint; although it may be a few loose instrument connections, or a poor terminal ground.

The defect may be localized by the following process:

Attach a ground wire to the middle of the line, and with the distant end opened, measure to the middle. If the bulk of the resistance is still in the half of the line measured, the defect is between the middle of the line and the testing station; now have the ground wire moved to the middle of the half measured, and make a third test, and so on until the trouble is passed, and the measured resistance makes a sudden fall from the last one; when this occurs, the defect is located between the last two measurements.

If, on the contrary, on making the first test with the middle of the line grounded, the resistance falls to such an amount as half of the line would normally possess, the defect is evidently in the open half of the line, beyond the middle ground wire, and must be followed up until it appears on the testing side of the temporary ground once more. Then it is located between the two last temporary terminals.

TO TEST FOR A GROUND WITH THE BRIDGE.

Have the grounded wire looped to a perfect wire at the distant station; connect the loop to rheostat posts 3 and 4, and measure it: call the resistance 4,500 ohms. Connect a ground wire to post 3, and

the perfect wire to post 4, and measure it, the distand end being grounded at the fault, and the defective wire open at the testing end. Call the resistance 3,050 ohms; then connect the defective wire to post 4, and measure to the fault, leaving the ground wire in post 3, and the good wire open. Call resistance 1,510 ohms.

Thus we have now three measurements; viz., the metallic loop, 4,500 ohms; the long end of the loop measured to ground at the fault, 3,050 ohms, and the short end, measured in the same way, 1,510 ohms. We might at first suppose that the two sides of the loop measured separately would, added together, give a sum equal to the resistance of the loop; but we see this is not so; that the sum of the two measurements is 4,560 ohms, or sixty ohms more than the resistance of the loop.

This surplus of 60 ohms, is evidently the resistance of the fault itself, measured twice over; once when we measured the long side of loop, and once when we measured the short side, and the true resistance of the fault is therefore 30 ohms.

To ascertain this, we add the two last measurements together, and from their sum deduct the first, dividing the result by 2; the final result being 30 ohms, which, as before stated, is the resistance of the fault.

Then the resistance between the testing station

and the fault is found, by deducting the resistance of the fault, from the measurement of the defective wire to ground at the fault; that is, deduct 30 from 1,510, leaving a line resistance of 1,480 ohms between the testing station and the ground.

If the ordinary resistance of the entire line, the number of stations, and the length of the line in miles are known, it is easy from the foregoing data, to calculate the approximate location of the ground.

Suppose each of the two lines to have in circuit, 5 relays of 150 ohms resistance, making a total resistance, when in good working order, as the loop measurement shows, of 2,250 ohms. Suppose also that the line is 100 miles long: this gives a mileage resistance of 22½ ohms, including the relays.

Then the distance between the testing station and the fault, is $65\frac{7}{9}$ miles; which, of course is determined by dividing the line resistance to the fault, 1,480 ohms, by the resistance per mile.

Such tests as these will be more simple, as well as more accurate, if the relays can be cut out of circuit before commencing to test.

TO TEST FOR A CROSS WITH A GALVANOMETER.

First. When the two crossed wires are very nearly identical in resistance.

As in the diagram, Figure 30, call No. 1 A, B: No. 2, C, D, and the cross X. We measure No. 1, from A to B, leaving No. 2 open at C and D, finding the resistance to be, say 2,000 ohms.

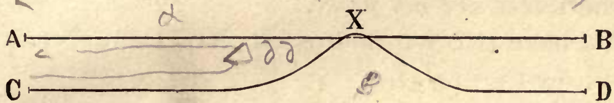

Figure 30.

Measuring A to D through the cross, leaving C and B open, we find this resistance 2,150 ohms. Then measuring A to C as a loop, leaving B and D open, we find the loop to have a resistance of 3,550 ohms.

The resistance of the cross itself is found by subtracting the result of the first measurement from that of the second; that is 2,000 from 2,150, and is thus 150 ohms: and the resistance from the testing station A to the cross X on No. 1, is now determined by deducting the resistance of the cross, *i. e.*, 150 ohms, from the loop measurement 3,550 ohms, and dividing the result by 2; giving as the required resistance 1,700 ohms.

This may be reduced to miles, in the manner ex-explained, in the test for grounds.

Suppose the lines are 100 miles long: since we found by measuring from A to B that the resistance of No. 1 with No. 2 open, was 2,000 ohms; it is

clear that 2,000 ohms is to 100 miles, as 1,700 ohms is to 85 miles, which is the distance of the cross X from the testing station A.

Second.—To test for a cross when the resistance of the *wires are not alike.*

We have two wires crossed, No. 1 and No. 2, as shown in Figure 31.

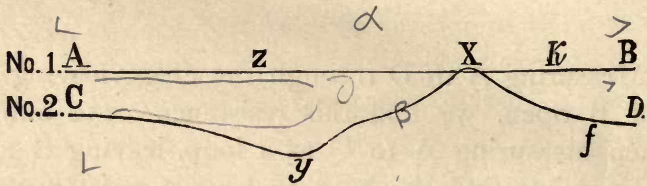

Figure 31.

Both wires have the same termini, but have different resistances. We desire to locate the cross X.

No. 1 we will again suppose to be 100 miles long. We proceed as follows:

Measure No. 1, A to B, with C and D open: call it 2,000 ohms. This is the regular resistance of No. 1.

Measure C to B, through the cross, A and D being left open, call it 2,750 ohms.

Measure now the loop from A, through the cross, and back to C, leaving B and D open; call it 3,100 ohms.

Call No. 1 on the near side of the cross Z, and on the far side K. Call also No. 2 on the near side of

the cross Y, and the resistance of the cross itself X.

Now, by examining the diagram, we may see that we have made measurements as follows: 1st, from A to B, 2,000 ohms, that is, the sum of the two sections Z and K; 2d, from C to B, 2,750 ohms, that is, the sum of Y, K and X; 3d, from A to C, 3,100 ohms, that is, the sum of Z, Y and X.

We now add the results of the first and third measurements, 2,000 and 3,100 ohms, together, the sum consisting of the following elements: Z measured twice, Y once, X once, and K once; or, No. 1 from A to the cross twice, No. 2 from C to the cross once, the cross itself once, and No. 1 from the cross to B once.

Next we subtract the result of the second measurement, 2,750 ohms, which consists, as we have seen, of Y, X and K, each measured once, that is, No. 2 from C to the cross once, the cross itself once, and No. 1 from the cross to B once, from the sum, 5,100 ohms, of the first and third; the remainder is, of course, 2,350 ohms, which represents that part of No. 1 which we have callen Z doubled; dividing that number by 2, we find the resistance of Z to be 1,175 ohms.

Then, as the length of the line is 100 miles, and the entire resistance from A to B, that is, the sum of Z and K, 2,000 ohms, it is clear that the resistance of Z, or the portion of the line between A and X,

must be 58¾ miles, for as 2,000 ohms is to 100 miles, so 1,175 ohms is to 58¾ miles, the distance of the cross from A.

TO TEST A TERMINAL GROUND AT A DISTANT STATION.

Measure any two lines to earth through the same ground wire.

Then measure the two wires looped together at the distant station.

Add together the resistances of the two lines when measured separately, and compare with the resistance of the loop.

If the resistance of the sum of the two is greater than that of the loop, the ground wire is not perfect, and its resistance is found by deducting the resistance of the loop from that of the sum of the separate measurements, and dividing the remainder by 2.

For example: We are at a testing station A; we desire to test the terminal ground at B. We measure No. 1 to ground at B, and find its resistance to measure 2,500 ohms.

Measuring No. 2, in the same way, we get a measured resistance of 3,600 ohms.

Disconnecting both wires from the distant ground, and connecting them as a loop, we measure the loop, and find the result to be 5,950 ohms.

The sum of the first two measurements, 2,500 and 3,600 ohms, is 6,100 ohms, which, as we see, is 150 ohms greater than the resistance of the loop.

The ground wire is, therefore, defective. To ascertain its resistance, we divide the remainder 150 by 2, which shows the resistance of the ground wire to be 75 ohms.

In all of the foregoing tests, when we measure a loop, the two wires of the loop are to be connected with the rheostat binding screws 3 and 4. When we measure a single line, we connect a ground wire with post 3, and the line with post 4. The battery and galvanometer are connected in their usual places.

TO MEASURE THE RESISTANCE OF AN ELECTRIC LIGHT.

Since it is often necessary to ascertain the resistance of an electric lamp while burning, it has been thought well to refer in conclusion to that subject. The measurement can be readily made by the Wheatstone Bridge apparatus, or by the use of a tangent galvanometer, although, of course, the fine instruments we have described are not adapted for use with the strong currents requisite in electric lighting.

When we deal with such currents, we have to employ galvanometers of very low resistance, and

rheostats and resistance coils composed of very large wire, and in some cases it is convenient to use resistances of other material, such as carbon.

Figure 32 shows a theoretical arrangement for measuring the resistance of an electric lamp.

The wires 1 and 2 lead from a suitable dynamo-electric machine M to the Bridge terminals.

In the branches A and C suitable resistances are placed as usual; the principal adjustable resistance is included in the branch B, and the lamp to be measured in D.

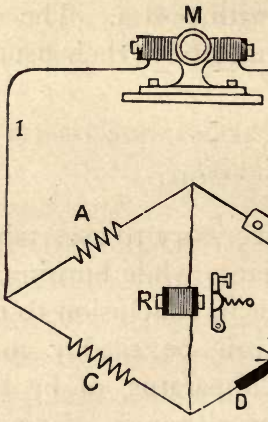

Figure 32.

It will generally be best to make the resistance in A larger than that in C, so that B will also have to be proportionately larger than the resistance of the lamp in D.

We thus cause the larger part of the current to pass through the branches C and D, and afford the necessary supply of electricity to the lamp. Instead of first using a galvanometer, it has been found advantageous to insert a relay R in the cross wire, until the balance is so nearly established, that the magnet does not seem to be affected. We can then safely substitute even a fine wire galvanometer, and conclude the measurement more accurately, calculating the result by proportion in the same way as we would in the measurement of any other resistance.

By using a polarized relay, we not only detect the passage of a current in the cross wire, but also its direction.

TABLE OF TANGENTS.

Degrees.	Tangents.	Degrees.	Tangents.	Degrees.	Tangents.	Degrees.	Tangents.
1.	.0175	13.	.2309	25.	.4663	37.	.7536
1.5	.0262	13.5	.2401	25.5	.4770	37.5	.7673
2.	.0349	14.	.2493	26.	4877	38.	.7813
2.5	.0437	14.5	.2586	26.5	.4986	38.5	.7954
3.	.0524	15.	.2679	27.	.5095	39.	.8098
3.5	.0612	15.5	.2773	27.5	5206	39.5	.8243
4.	.0699	16.	.2867	28.	.5317	40.	.8391
4.5	.0787	16.5	.2962	28.5	5430	40.5	.8541
5.	.0875	17.	.3057	29.	.5543	41.	.8693
5.5	.0963	17.5	.3153	29.5	.5658	41.5	.8847
6.	.1051	18.	.3249	30.	.5774	42.	.9004
6.5	.1139	18.5	.3346	30.5	.5890	42.5	.9163
7.	.1228	19.	.3443	31.	.6009	43.	.9325
7.5	.1317	19.5	.3541	31.5	.6128	43.5	.9490
8.	.1405	20.	.3640	32.	.6249	44.	.9657
8.5	.1495	20.5	.3739	32.5	.6371	44.5	.9827
9.	.1584	21.	.3839	33.	.6494	45.	1.
9.5	.1673	21.5	.3939	33 5	.6619	45.5	1.0176
10.	.1763	22.	.4040	34.	.6745	46.	1.035
10.5	.1853	22.5	.4142	34.5	6873	46.5	1.053
11.	.1944	23.	.4245	35.	.7002	47.	1.072
11.5	.2035	23.5	.4348	35.5	.7133	47.5	1.091
12.	.2126	24.	.4452	36.	.7265	48.	1.110
12.5	.2217	24.5	.4557	36.5	.7400	48.5	1.130

Table of Tangents—*Continued.*

Degrees.	Tangents.	Degrees.	Tangents.	Degrees.	Tangents.	Degrees.	Tangents.
49.	1.150	59.5	1.697	70.	2.747	80.5	5.975
49.5	1.170	60.	1.732	70.5	2.823	81.	6.313
50.	1.191	60.5	1.767	71.	2.904	81.5	6.691
50.5	1.213	61.	1.804	71.5	2.988	82.	7.115
51.	1.234	61.5	1.841	72.	3.077	82.5	7.595
51.5	1.257	62.	1.880	72.5	3.171	83.	8.144
52.	1.279	62.5	1.921	73.	3.270	83.5	8.776
52.5	1.303	63.	1.962	73.5	3.375	84.	9.514
53.	1.327	63.5	2.005	74.	3.487	84.5	10.385
53.5	1.351	64.	2.050	74.5	3.605	85.	11.430
54.	1.376	64.5	2.096	75.	3.732	85.5	12.706
54.5	1.401	65.	2.144	75.5	3.866	86.	14.300
55.	1.428	65.5	2.194	76.	4.010	86.5	16.349
55.5	1.455	66.	2.246	76.5	4.165	87.	19.081
56.	1.482	66.5	2.299	77.	4.331	87.5	22.903
56.5	1.510	67.	2.355	77.5	4.510	88.	28.636
57.	1.539	67.5	2.414	78.	4.704	88.5	38.188
57.5	1.569	68.	2.475	78.5	4.915	89.	57.290
58.	1.600	68.5	2.538	79.	5.144	89.5	114.588
58.5	1.631	69.	2.605	79.5	5.395	90.	
59.	1.664	69.5	2.674	80.	5.671		

TABLE OF SINES.

Degrees.	Sines.	Degrees.	Sines.	Degrees.	Sines.	Degrees.	Sines.
1.	.0175	12.	.2079	23.	.3907	34.	.5592
1.5	.0262	12.5	.2164	23.5	.3987	34.5	.5664
2.	.0349	13.	.2250	24.	.4067	35.	5736
2.5	.0436	13.5	.2334	24.5	.4147	35.5	.5807
3.	.0523	14.	.2419	25.	.4226	36.	.5878
3.5	.0610	14.5	.2504	25.5	.4305	36.5	.5948
4.	.0698	15.	.2588	26.	.4384	37.	.6018
4.5	.0785	15.5	2672	26.5	.4462	37.5	.6088
5.	.0872	16.	.2756	27.	.4540	38.	.6157
5.5	.0958	16.5	.2840	27.5	.4617	38.5	.6225
6.	.1045	17.	.2924	28	.4695	39.	.6293
6.5	.1132	17.5	.3007	28.5	.4772	39.5	.6361
7.	.1219	18.	.3090	29.	.4848	40.	.6428
7.5	.1303	18.5	.3173	29.5	.4924	40.5	.6494
8.	.1392	19.	.3256	30.	.5000	41.	.6561
8.5	.1478	19.5	.3338	30.5	5075	41.5	.6626
9.	.1564	20	.3420	31.	.5150	42.	.6691
9 5	.1650	20.5	.3502	31.5	.5225	42.5	.6756
10.	.1736	21.	3584	32.	.5299	43.	.6820
10.5	.1822	21.5	.3665	32.5	.5373	43.5	.6884
11.	.1908	22.	.3746	33.	.5466	44.	.6947
11.5	.1994	22.5	.3827	33.5	.5519	44.5	.7009

TABLE OF SINES—*Continued.*

Degrees.	Sines.	Degrees.	Sines.	Degrees.	Sines.	Degrees.	Sines.
45.	.7071	56.5	.8339	68.	.9272	79.5	.9833
45.5	.7133	57.	8387	68.5	.9304	80.	.9848
46.	7193	57.5	.8434	69.	.9336	80.5	.9863
46.5	.7254	58.	.8480	69.5	9367	81.	.9877
47.	.7314	58.5	.8526	70.	.9397	81.5	.9890
47.5	.7373	59.	.8572	70.5	.9426	82.	.9903
48.	.7431	59.5	.8616	71.	9455	82.5	.9914
48.5	7490	60.	.8660	71.5	.9483	83.	.9925
49.	.7547	60.5	.8704	72.	.9511	83.5	.9936
49.5	.7604	61.	.8746	72.5	.9537	84.	.9945
50.	.7660	61.5	.8788	73.	.9563	84.5	.9954
50.5	.7716	62.	.8829	73.5	.9588	85.	.9962
51.	.7771	62.5	.8870	74.	.9613	85.5	.9969
51.5	.7826	63.	.8910	74.5	.9636	86.	.9976
52.	.7880	63.5	.8949	75.	.9659	86.5	.9981
52.5	.7934	64.	.8988	75.5	.9681	87.	.9986
53.	.7986	64.5	9026	76.	.9703	87.5	.9990
53.5	.8039	65.	9063	76.5	.9724	88.	.9994
54.	.8090	65.5	.9100	77.	.9744	88.5	.9997
54.5	.8141	66.	.9135	77.5	9763	89.	.9998
55.	.8192	66.5	.9171	78.	.9781	89.5	1.
55.5	.8241	67.	.9205	78.5	9799	90.	1.
56.	.8290	67.5	.9239	79.	.9816		